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THE JOURNAL OF GEOLOGY

March 1951

GLACIAL HISTORY OF WOLF CREEK, ST. ELIAS RANGE, CANADA[1]

ROBERT P. SHARP
California Institute of Technology

ABSTRACT

Remnants of late Wisconsin drift on bedrock benches 800–1,500 feet above Wolf Creek are the oldest evidence of glaciation recognized. Deposits of very latest Wisconsin and possibly, in part, earliest post-Wisconsin drift are the product of a limited advance or extended pause in recession from the late Wisconsin climax. Wolf Glacier was then at least several hundred feet thicker, and its terminus was not less than 4 or 5 miles beyond the present snout. Post-Wisconsin xerothermic conditions caused extensive ice shrinkage, and the glaciers become smaller than at present. During this period an extensive valley train was formed, alluvial cones and fans were built, and a mature white spruce forest developed up-valley to its natural tree line. A subsequent expansion and readvance culminated between 1840 and 1890. Large raw lateral and terminal moraines and a trim line in the mature spruce forest are the principal manifestations of this advance, which is believed to be of climatic, rather than of orogenic or seismic, origin. Subsequently shrinkage, recession, and stagnation have ruled. The lower 9 miles of Wolf Glacier are stagnant, and this section has experienced 350–500 feet of vertical ablation, with terminal recession of only a few hundred yards. Degradation was interrupted by expansion and advance of certain favorably situated ice streams, starting in the late 1930's and extending into the 1940's. Slight rejuvenation also occurred in the uppermost stagnant part of Wolf Glacier. This reactivation was on the wane by 1947 and appears to have been but a minor interruption in the general shrinkage and degradation of the last fifty to a hundred years. Analysis of records suggests a climatic, rather than a seismic, cause for this recent rejuvenation.

INTRODUCTION

GENERAL STATEMENT

Studies of glaciers and glaciation on interior flanks of Alaska-Yukon mountain ranges have not kept pace with investigations in coastal areas. This is unfortunate, for the interior offers promise of yielding better data on Wisconsin and earlier glacial stages and the details of post-Wisconsin history worked out along the coast should be extended inland. The Alaska-Yukon hinterland provides a fertile field for glacier studies which is barely scratched by earlier investigations or by this work on Wolf Creek. Much remains to be done, but it is hoped that this report will arouse interest and start off in the right direction.

Field studies extended from June 26 to September 6, 1941, as an endeavor of the fourth Wood Yukon Expedition sponsored by the American Geographical Society and directed by Walter A. Wood. Supplementary data are derived from Wood expeditions of 1935, 1936, and 1939 and a subsequent trip by the Woods in 1947. Photogrammetrical mapping from high-oblique air and ground photographs has been a primary objective of these expeditions. Consequently, a number of fixed photo stations have been occupied repeatedly between 1935 and 1947, and a valuable record of glacier changes has been made.

[1] Manuscript received May 27, 1950.

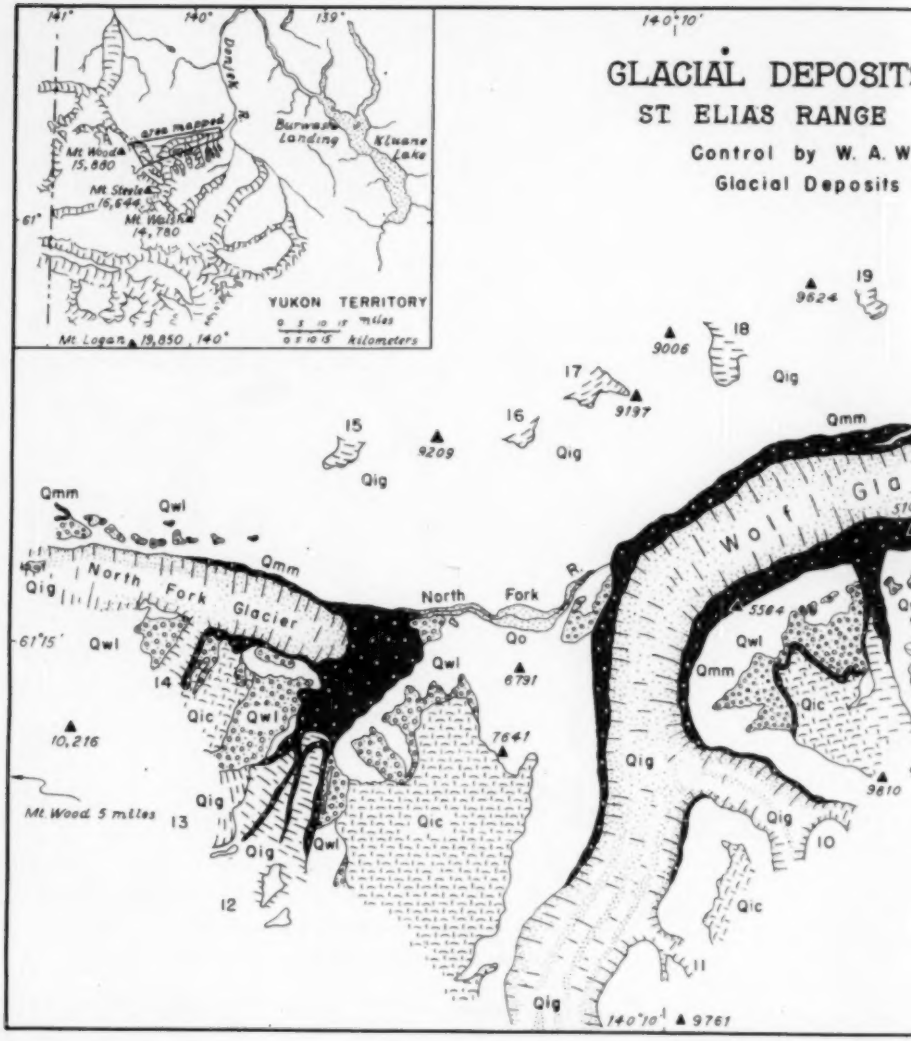
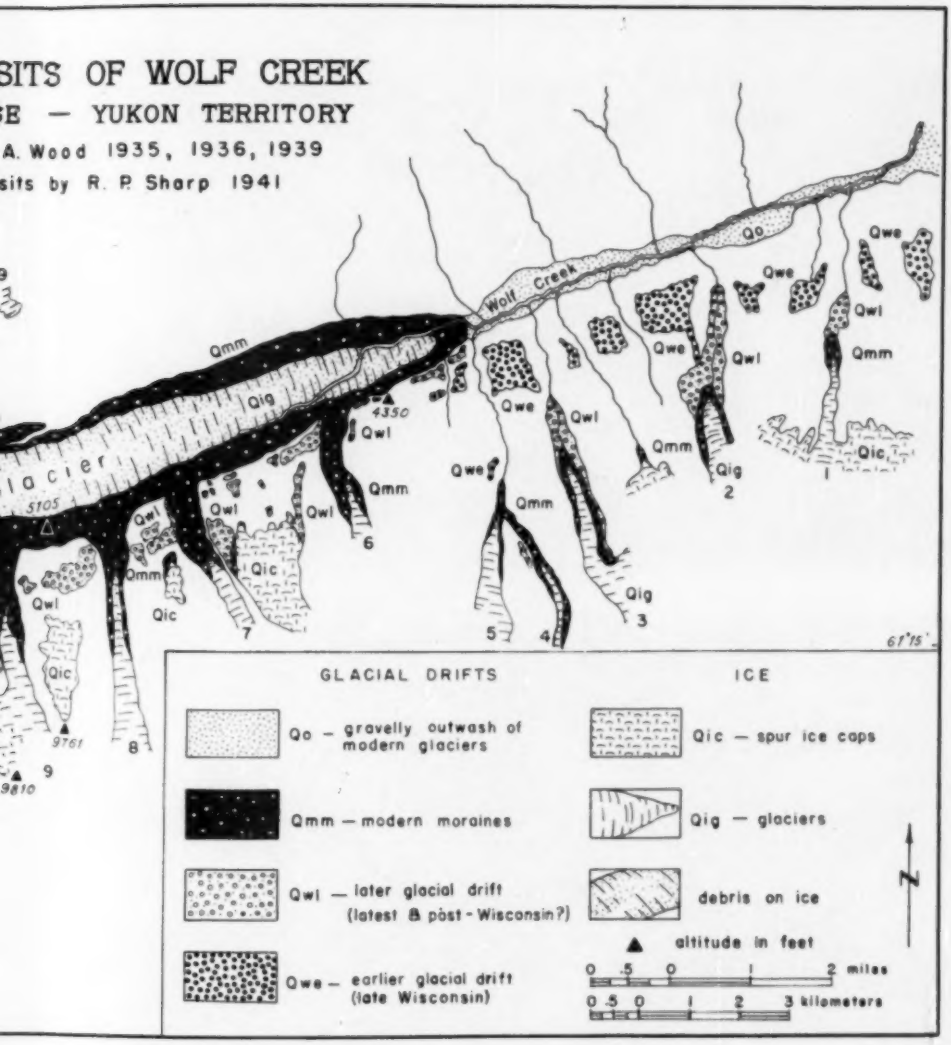


FIG. 2.—Map of glaciers and



and glacial deposits along Wolf Creek

LOCATION AND PHYSICAL SETTING

Wolf Creek is in Yukon Territory, Canada, about 25 miles east of the Alaska border, at 61°15′ N. and 140°10′ W. (fig. 1). It lies on the northeastern flank of the Ice Field Ranges (Bostock, 1948, pp. 92–101), a group of lofty peaks termed "the bend" for purposes of location. The valley is 4,000–5,000 feet deep, with floor altitudes of 3,500–6,500 feet in the area mapped (fig. 2). Flanking peaks and ridges rise to 11,000 feet, and just to the west and southwest Wolf Creek heads against Mount Wood (15,880) and

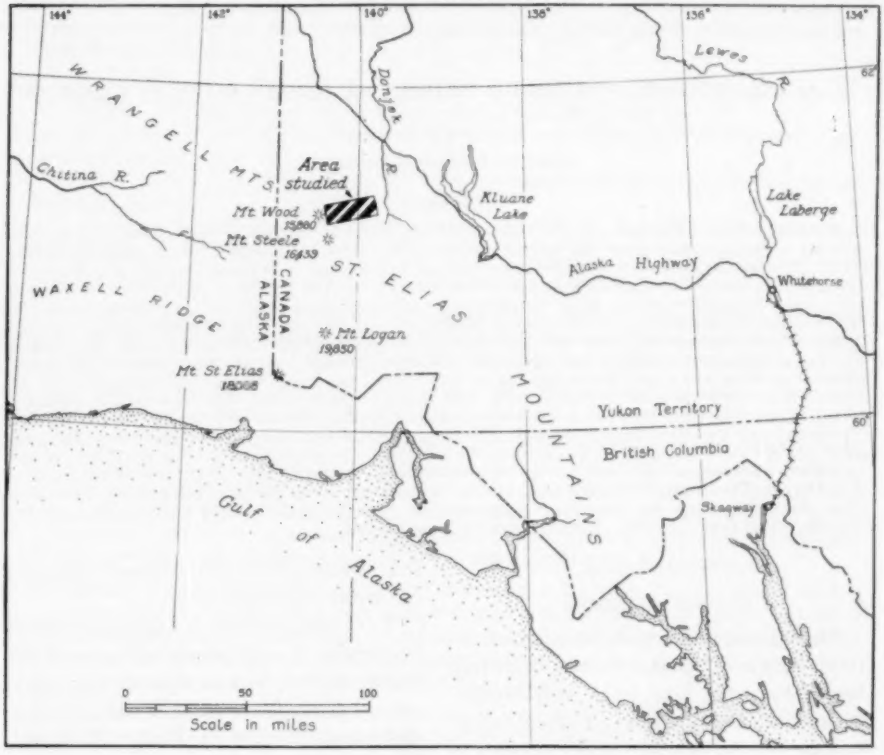


FIG. 1.—Location map of Wolf Creek area

within the northwest-trending St. Elias Mountains.

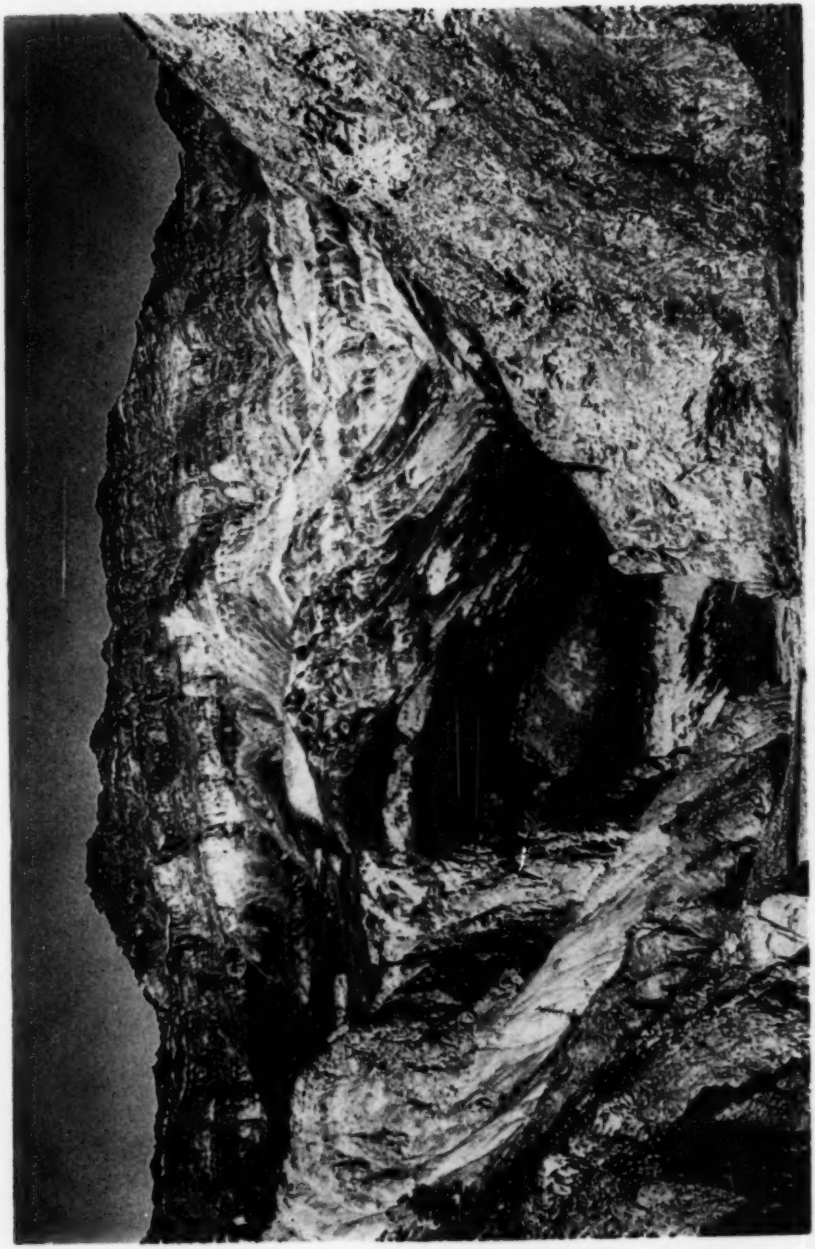
Wolf Creek is a branch of Donjek River, a tributary of the White, which empties into the Yukon. Its valley is a broad U-shaped trough with a nearly straight west-southwesterly course for the first 15 miles to the mid-point, where it makes a sharp southward curve, herein Mount Steele (16,644). Timber line is about 4,500 feet, and fully 90 per cent of the area mapped is treeless, although scrub willow and tundra vegetation grow to 6,000–7,000 feet. The high country has a perennial mantle of ice and snow, and orographic snow line lies at 8,000–9,100 feet.

Climatologically the environment is

A

B

Aerial views of Wolf Creek

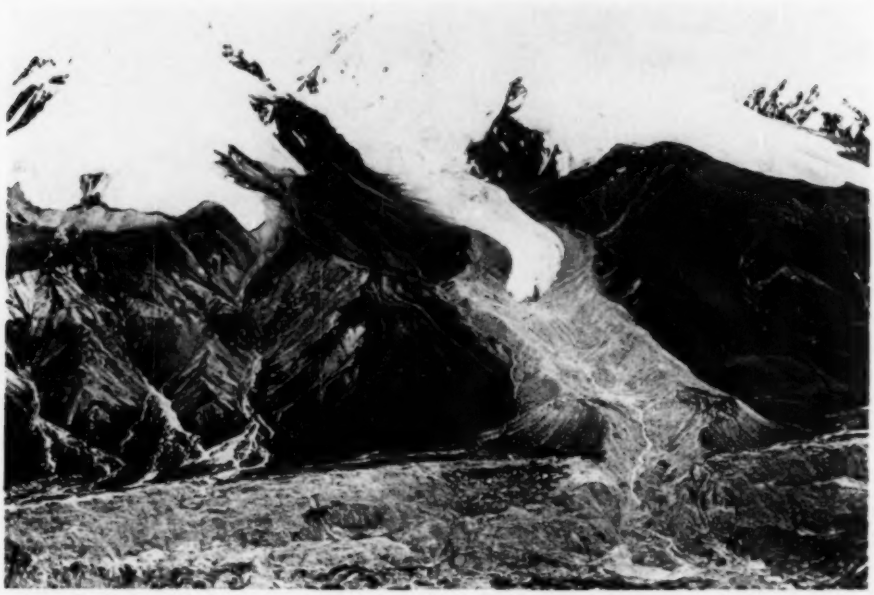


Unglaciated rock gorge

A

B

Alluvial cones and end moraines



A

B

Receding and stagnant glaciers

continental and semiarid, for high mountains to the southwest shut off moisture from the Gulf of Alaska. The nearest weather station at Burwash Landing, 45 airline miles east, records a mean annual precipitation of about 10 inches and summer maximum temperatures approaching 80° F. Other Yukon Plateau stations at Atlin, Carcross, and Whitehorse,[2] report similar conditions. The higher parts of Wolf Creek probably receive heavier precipitation, but, compared to the Alaskan coastal region with mean annual precipitation well in excess of 100 inches, this is a dry area.

CONSTITUTION OF THE GLACIER SYSTEM

The Wolf Creek system consists of a trunk glacier,[3] 25 miles long by 1.5 miles wide, with approximately thirty connected and disjuncted tributaries. Tributaries shown on the map (fig. 2) have been numbered from 1 to 19 in clockwise order for ease of reference. Spurs between tributary canyons, especially on the south wall, are mantled by caps of ice covering a few square miles and attaining a thickness of 100–250 feet (pls. 1, *B*; 4, *A*). These caps partake of some movement and build low moraines, and their products must be distinguished carefully from the work of valley glaciers.

[2] Climatological data kindly furnished by the 7th Weather Group, U.S Air Force.

[3] In earlier reports the trunk ice stream was termed "Wolf Creek Glacier." Bostock (1948, p. 99) more properly calls it "Wolf Glacier," and that usage is followed here.

GLACIAL HISTORY

INTRODUCTORY STATEMENT

The record of Wisconsin and older glaciations in the Yukon and Alaska should be sought near the outer limit of glaciation on the interior flanks of the St. Elias, Alaska, and other such ranges, because here the glaciers advanced onto a semiarid land surface rather than into the sea. Although Wolf Creek lies on the

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PLATE 1

A, Looking west-southwest up Wolf Creek. Wolf Creek fan projecting into Donjek Valley just beyond foreground ridge, open-valley benches on south wall of lower Wolf Creek, Mount Steele (16,644) at left corner skyline and Mt. Wood (15,880) on center skyline. Photo by W. A. Wood, 1941.

B, View east-northeast down Wolf Creek approximately from edge of map area (fig. 2). Snout of North Fork Glacier to lower left, glacier 10 with prominent medial moraines right margin above center, stagnant Wolf Glacier in center distance. Photo by W. A. Wood, 1941.

PLATE 2

Looking north down unglaciated rock gorge cut by tributary stream into open-valley bench on south wall of lower Wolf Creek below glaciers 4 and 5 (fig. 2).

PLATE 3

A, Current (barren) and ancient (forested) alluvial cones on north wall of lower Wolf Creek. Ancient cone formed during post-Wisconsin xerothermic interval. Modern valley train of Wolf Creek in foreground (1941).

B, Wolf Glacier terminal moraine formed during modern advance culminating fifty to a hundred years ago. Note contrast between scanty vegetation on moraine and mature white spruce forest on adjacent slopes (1941).

PLATE 4

A, Modern moraine of receding tributary glacier 9 on south wall of Wolf Creek. Spur ice caps on either side and stagnant Wolf Glacier in foreground (1941).

B, Looking down onto stagnant Wolf Glacier from north wall. Modern moraines of glacier 8 (*upper left*) and of glacier 9 (*upper right*). Wolf Glacier about 1 mile wide, 300–400 feet of down-melting represented (1941).

interior flank of the St. Elias Range, it is not ideally situated for such studies, as it is fully 75 miles from the outer limit of the last well-marked glaciation (Cairnes, 1917; Capps, 1931, pl. 2), presumably a phase of the Wisconsin. All glacial deposits mapped on Wolf Creek are Wisconsin and younger. Evidence of an earlier (Bostock, 1936, pp. 9–10, 48) and more extensive advance is found in widely separated parts of the Yukon,[4] but correlation and dating of the earlier glaciation are not yet possible. The scarcity of pre-Wisconsin drift throughout Alaska (Capps, 1931, pp. 6–7) has been attributed to its removal by erosion or burial by later advances (Capps, 1916, p. 63). Table 1 outlines the glacial history of Wolf Creek.

TABLE 1

CHRONOLOGICAL OUTLINE OF WOLF CREEK GLACIAL HISTORY

Event	Feature	Date
Present regimen	Shrinkage, retreat, stagnation; local expansion, advance, and reactivation; valley train, moraine, alluvial-fan and cone-building	Continuing
Modern advance	Raw moraines sparsely vegetated	Culmination between A.D. 1840 and 1890
Post-Wisconsin xerothermic interval	Retreat of glaciers; valley train, alluvial fans, and cones built; forest development	Approximately 2,000–6,000 B.C.
Later glaciation	Fresh moraines and drift deposits on valley walls 50–1,000 feet above present glaciers	Latest—and post-(?)—Wisconsin
Earlier glaciation	Drift deposits on walls of lower Wolf Creek, 800–1,500 feet above valley floor	Late Wisconsin

OPEN-VALLEY STAGE

Discussion of this physiographic problem is essential to an understanding of the glacial history. Broad remnants of a bedrock bench, 0.5–0.75 mile wide and thinly mantled by till and gravel, are preserved on the south wall of lower Wolf Creek (pl. 1, *A*). The position, form, and gentle northward slope of these remnants indicate that they were once part of a broad U-shaped valley, graded to a course 700–800 feet above the present stream. The upper courses of south-wall tributaries are graded to the same level, but their lower parts are deeply entrenched below it. Narrow remnants of the bedrock bench extend upstream along the south wall to the bend, and the North Fork continues the open-valley form westward to its head. Suggestions of the bench are also seen along the north wall of Wolf Creek. Cement Creek, next north of Wolf Creek, displays a much less dissected open-valley form, and air photographs show extensive remnants along other near-by streams. These regional aspects and the lack of any consistent relation between open-valley remnants and bedrock structure lead to the conclusion that this is a feature of historical significance.

For reasons given later, dissection of the open valley is thought to have occurred prior to the late Wisconsin, although its remnants were buried by late

[4] Personal communication, H. S. Bostock.

Wisconsin ice. Truncated spurs backing the open valley and its U-shape may have been formed by the late Wisconsin glacier or possibly by some predissection glaciation. In brief, a broad valley, 700–800 feet above present stream grade, was developed along Wolf Creek by stream and possibly glacial erosion. It was dissected by streams prior to advance of the late Wisconsin glacier which filled Wolf Creek to a level above the open-valley remnants, possibly modifying them and leaving thereon a mantle of drift.

EARLIER GLACIATION (LATE WISCONSIN)

Deposits.—Till and glacifluvial debris left by the earlier glaciation are most extensive on the south side of Wolf Creek below the snout of Wolf Glacier (fig. 2). Drift high on the valley walls farther upstream may have been deposited at this time, but much of it has subsequently been reworked by spur ice caps. The till contains stones of granite, diabase, limestone, marble, schist, phyllite, and quartz. Its glacial origin is demonstrated by striated facets on rock fragments and by the typical form and position of lateral moraines along tributary canyons. The drift is considered older than other glacial deposits in the area because of low boulder frequency,[5] subdued topographic expression, and elevated position. Most of it lies on benchlike remnants of the open-valley stage 800–1,500 feet above the present valley floor, and some deposits at the mouth of Wolf Creek are 2,000 feet above existing stream grade.

Age of earlier glaciation.—If this glaciation were pre-Wisconsin, no Wisconsin glacier in lower Wolf Creek could have been more than 1,000 feet thick because it would have removed, reworked, or buried the older drift. The Wisconsin Wolf Glacier was tributary to Donjek Glacier, which extended fully 75 miles (Cairnes, 1917; Capps, 1931, pl. 2) below the mouth of Wolf Creek. Wolf Glacier must have been at least as thick as Donjek Glacier, for the floors of the two valleys are accordant. Even with a steep gradient and gravity flowage (Demorest, 1942, pp. 32–34), it is hard to conceive of a glacier only 1,000 feet thick extending 75 miles down Donjek Valley. Many valleys in Alaska contained Wisconsin glaciers at least 5,000 feet thick (Capps, 1931, p. 4; Moffit, 1938, p. 113), and, although these glaciers may have been larger than Donjek Glacier, they were probably not five times larger. Therefore, a pre-Wisconsin age for the earlier drift along Wolf Creek is discounted.

Earliest Wisconsin glaciers (Iowan) were extensively developed in far western mountains of the United States (Fryxell, 1930, pp. 44–72; Blackwelder, 1931, pp. 884–895, 906–918; Horberg, 1940, pp. 296–298; Antevs, 1945, pp. 17–25). The Keewatin and Cordilleran ice masses are also thought to have experienced expansion at this time (Antevs, 1945, pp. 8–14), although this view is not universal (Flint, 1943, pp. 346–358; Flint and Dorsey, 1945). An earliest Wisconsin age for the earlier drift on Wolf Creek was once favorably considered because of these relations (Sharp, 1941, p. 1933), but that view is now abandoned for the same reasons that discount a pre-Wisconsin age. The Wolf and Donjek glaciers were simply too large in the late Wisconsin for this drift to be any older.[6] Local orogenic up-

[5] "Boulder frequency" (Blackwelder, 1931, pp. 878–880) refers to the number of boulders of specified lithology and size per unit area on the surface of a drift deposit. Other conditions being equal, boulder frequency is inversely proportional to age. Exact counts were not made on Wolf Creek, but the contrast in boulder frequencies of earlier and later deposits was readily apparent.

[6] Hugh S. Bostock, of the Geological Survey of Canada, effectively established this point in a kindly letter of May 11, 1942.

lift of the St. Elias Mountains by as much as 5,000 feet during the Pleistocene, as suggested (I. C. Russell, 1891, pp. 172, 175; Smith, 1939, p. 69), might have caused a greater extent of glaciers in the late Wisconsin (Capps, 1916, p. 6) than during some of the preceding advances.

If the foregoing dating is accepted, narrow rock gorges (pl. 2) cut 500–1,000 feet below the level of earlier drift on open-valley benches along the south wall of lower Wolf Creek present a problem. These gorges are clearly stream-cut and unglaciated. Two interpretations are considered: (1) The gorges were cut after the drift was deposited and no subsequent glaciers entered the gorges, or (2) they were cut prior to deposition of the drift and were protected from glaciation by a filling of gravel, immobile ice, or both.

If the drift on the open-valley benches is no older than late Wisconsin, the first interpretation requires that the gorges be cut 500–1,000 feet into a schist-phyllite-marble complex by relatively small streams after the late Wisconsin. This far exceeds the 25–50 feet of bedrock dissection occurring since the late Wisconsin in other glaciated mountains (Blackwelder, 1931, pp. 873, 883, 893; Page, 1939, pp. 796, 813). Furthermore, at least one of the rock gorges had about its present depth by very latest Wisconsin or earliest post-Wisconsin, for glacier 2 (fig. 2) extended a short distance into it at that time. If the gorges are of late Wisconsin age, this would require that they be cut between the earlier and later glaciation recognized along Wolf Creek. This interval is thought to be much too short to permit 500–1,000 feet of bedrock dissection.

For these reasons, it is felt that gorge-cutting preceded the late Wisconsin glaciation, so an exploration of the possible nature and origin of the filling protecting the gorges from ice scour is in order. If the filling were ice, it would have to develop *in situ* because ice moving into the gorges from either end would produce unmistakable modifications. Drifted snow and overflow ice may have composed part of the filling, but much of it was probably gravel. Outwash from glaciers lying farther up the tributary valleys provides a suitable source of gravel, and its accumulation could have been caused by extension of the trunk glacier across the mouths of the tributary gorges. Gravel fillings 1,000 feet thick developed during the glacial period in canyons near Kluane Lake (Cairnes, 1915, pp. 20–21). The greatest weakness of this hypothesis is the lack of remnants or traces of any such gravel filling along Wolf Creek tributaries, but possibly interbedded masses of ice facilitated complete flushing-out during the subsequent climatic amelioration.

Thus the earlier glaciation on Wolf Creek is dated as late Wisconsin in relation to previous work in Alaska (Capps, 1931, p. 6) and the Yukon.[7] A working hypothesis proposes that the deep rock gorges of the tributary canyons were protected from glaciation by a filling of gravel and of ice developed *in situ*. If this hypothesis is fallacious, ideas concerning the amount of bedrock dissection possible for relatively small streams in the post-Wisconsin interval will have to be radically revised.

LATER GLACIATION (LATEST WISCONSIN AND EARLIEST POST-WISCONSIN?)

Description.—Drift of this glaciation is located principally on the floors of tributary valleys 1, 2, and 3, along the trunk valley outside of and 50–1,000 feet

[7] Personal communication, H. S. Bostock.

above the modern moraines, and in the triangular area between Wolf Creek and its North Fork (fig. 2). The sparseness of drift on the north side of Wolf Creek is due principally to steep slopes which promote rapid removal of loose morainal materials. Drift of this glaciation is distinguished from older deposits by its greater boulder frequency, youthful glacial topography, slight weathering, topographic position, and lack of extensive dissection. In areas below timber line it is easily separated from raw modern moraines by dense growths of mature spruce. Topographic relations are particularly diagnostic along the tributary valleys of lower Wolf Creek, where the subdued lateral moraines of the earlier glaciation rest high on the valley walls and drift of the later glaciation lies below on the valley floor. Erosion by streams marginal to the trunk glacier during this phase is also clearly evident on the walls of the trunk valley.

During the later glaciation the trunk glacier was at least several hundred feet thicker than at present, but its terminal position is not indicated by an end moraine. As in other areas (Moffit and Knopf, 1910, p. 38; 1938, p. 101; Capps, 1916, p. 80; Speight, 1940, pp. 140–142), this is attributed to vigorous outwash activity on the valley floor. North Fork Glacier and all south-wall tributaries above the present terminus of Wolf Glacier joined the trunk glacier during this phase, but no tributary ice stream below the snout of Wolf Glacier reached the main valley.

High, relatively fresh areas of till in upper Wolf Creek are probably deposits of earlier drift surficially reworked by spur caps during the later glaciation. This is best shown in the area partly covered by a large spur cap west of Wolf Glacier above the bend (fig. 2). Here fresh till containing granitic boulders rests on Tertiary volcanics. The granitic debris could have come only from the south, southwest, or west, and Wolf Glacier or ice draining eastward from Mount Wood would have had to thicken by at least 1,500 feet to overwhelm this area. This it undoubtedly did during earlier advances but not during the later glaciation. The fresh till is earlier drift reworked surficially by the expanded spur cap during the later glaciation. A large area of later drift, in part of glacifluvial origin, on the south wall of Wolf Creek just east of the bend (fig. 2) has experienced a similar history.

Age of later glaciation.—This phase was less extensive and considerably later than the earlier glaciation. Whether the ice readvanced or simply maintained a condition of equilibrium for an extended period during recession from the late Wisconsin climax cannot be determined. However, the extent and nature of the deposits show that a distinct chapter in the glacial history is represented.

Such a phase could be very latest Wisconsin or possibly post-Wisconsin. In the Coast Ranges of northern British Columbia, Kerr (1936, p. 697) recognizes a post-Wisconsin glaciation more extensive than a subsequent advance, probably correlative with the modern advance on Wolf Creek, to be described shortly. In many other areas the post-Wisconsin featured an extended recession, which was terminated by an advance that generally is the most extensive of the post-Wisconsin interval (Kinzl, 1932, p. 396; Ahlmann, 1948, p. 74). Very late Wisconsin advances of the North American ice sheet at Iroquois Falls and Cochrane in Ontario (Antevs, 1928, pp. 154–155; 1931, p. 4) may be related to the Fennoscandian moraine in northern Europe and to late stages of

glaciation in the Alps (Zeuner, 1945, p. 53). Correlation of the later glaciation on Wolf Creek with these stages is not possible, but they do tip the balance in favor of a latest Wisconsin rather than a post-Wisconsin age for this glacial phase.

The post-Wisconsin interval in North America is estimated by Antevs (1931, p. 2) as approximately 8,700 years. Russell Glacier, 50 miles west of Wolf Creek, occupied a position 8 miles in advance of its present terminus 8,000 years ago (Capps, 1916, p. 74; 1931, p. 6). The maximum Wisconsin advance of Wolf and Donjek glaciers was a little more than half that of the Russell, so the snout of Wolf Glacier at the close of the Wisconsin should have been 4 or 5 miles in advance of the present terminus if the same proportions were maintained. Thus some of the drift deposited low on the walls of Wolf Creek during recessional phases of the later glaciation may be post-Wisconsin.

In brief, the later glaciation represents a pause or readvance interrupting recession from the late Wisconsin climax. Wolf Glacier was at least several hundred feet thicker and its terminus probably more than 4 or 5 miles in advance of the present glacier snout at this time, but no end moraine marks its position. Expanded spur caps reworked high deposits of drift left by the earlier glaciation. A very latest Wisconsin age is favored by analogy with other areas, but some of the recessional deposits may be earliest post-Wisconsin.

POST-WISCONSIN XEROTHERMIC INTERVAL

Geological, botanical, and paleoclimatological researches in Europe and North America demonstrate that post-Wisconsin climates were at one time warmer and presumably drier than at present (Bryan, 1932, pp. 76–81; Hotchkiss and Ingersoll, 1934, pp. 119–121; Wright, 1937, p. 443; Antevs, 1938, pp. 190–191; 1948, pp. 174–176; Lichtenecker, 1940; R. J. Russell, 1941, pp. 89–90; Cooper, 1942*b*, pp. 981–984; Hansen, 1946, pp. 729–731; Flint, 1947, pp. 487–499; Deevey, 1949, p. 1360). This period of ameliorated climate has been referred to as the "middle post-Pleistocene optimum," the "postglacial optimum," the "climatic optimum," or the *Postglazial Wärmezeit*. "Post-Wisconsin xerothermic period or interval" (Deevey, 1949, p. 1360) is favored here, as it is more in keeping with the concept of the post-Wisconsin as a possible interglacial stage within the Pleistocene and with the suggestion to abandon such terms as "post-Pleistocene" and "postglacial" (Flint, 1942*a*, pp. 570–571). Limiting dates assigned to the xerothermic period are of wide range (Flint, 1947, pp. 487–499; Antevs, 1948, pp. 174–176; Deevey, 1949, p. 1360), but for present purposes 7,000–8,000 years ago may be taken as the beginning (Antevs, 1925, p. 64; 1936, pp. 214–215; Hansen, 1946, p. 729) and 4,000 years ago as the approximate end (Matthes, 1942*a*, pp. 210–211; 1942*b*, p. 377).

Three or four thousand years of warm dry climate would certainly produce glacier recession, and Kerr (1936, pp. 684–696) ascribes a considerable retreat of Coast Range glaciers in British Columbia to a warm era, presumably the post-Wisconsin xerothermic interval. Matthes (1939, pp. 519–520; 1940, pp. 398–402) suggests that most mountain glaciers in western United States, except some chiefly on Mount Rainier and in the Olympic Mountains, were completely destroyed at this time and that the present glaciers are largely the product of more recent cooler and moister conditions. Remnants of buried forests uncov-

ered by glacier recession along the Alaskan coast (Reid, 1896, pp. 438–439; Gilbert, 1910, p. 103; Cooper, 1931, pp. 88–93; Wentworth and Ray, 1936, pp. 888, 891; Field, 1937, p. 78) are recognized as proof of an extensive post-Wisconsin retreat (Cooper, 1937, pp. 38–39), which permitted trees to grow far above present glacier snouts. Cooper (1942*a*, p. 18; 1942*b*, pp. 982–983; 1942*c*, p. 433) attributes this recession to post-Wisconsin xerothermic conditions. The magnitude and duration of the recession are not known, but climax forests estimated to be at least two thousand years old are being uncovered at the snouts of glaciers which have receded 45 miles from their maximum post-Wisconsin advance.

Glaciers on the interior side of the St. Elias Range experienced a similar post-Wisconsin recession (Tarr and Martin, 1914, p. 195), in which Wolf Creek glaciers presumably participated, although the evidence is not so clear as one might desire. The sparseness and extreme youth of vegetation on the present terminal moraine of Wolf Glacier (pl. 3, *B*), when compared to the mature spruce forest growing on adjacent slopes, suggest that the ice receded far enough up-valley to permit development of the spruce forest close to its natural timber line before readvance brought the glacier to its present position. This retreat, although of unknown magnitude and duration, may, by analogy, be assigned to the post-Wisconsin xerothermic period.

During the current deterioration of glaciers, Wolf Creek is actively aggrading its floor with a great raw outwash train. Simultaneously, tributary streams are building alluvial cones and fans onto this valley train (pl. 3, *A*), and Wolf Creek is building an alluvial fan on the floor of Donjek Valley (pl. 1, *A*). Remnants of heavily forested, larger, and higher alluvial cones and fans in Wolf and Donjek valleys are attributed to corresponding aggradation during the post-Wisconsin xerothermic interval. Wood (1936, p. 235) has noted that the modern Wolf Creek fan in Donjek Valley is being built over an older fan, and two ages of fans and cones are clearly evident at mouths of streams tributary to Wolf Creek (pl. 3, *A*). Isolated islands of trees on the floor of Wolf Creek probably represent remnants of the post-Wisconsin xerothermic valley train. If the present cycle of alluviation continues, many of the older post-Wisconsin features will be buried, just as they, in turn, may have buried still earlier forms.

The post-Wisconsin xerothermic interval is thought to have caused a notable recession of Wolf Creek glaciers, to have permitted the building of extensive valley trains and alluvial fans or cones, and to have promoted the growth and development of a spruce forest in Wolf Creek to at least 1.5 miles above the present snout of the trunk glacier.

MODERN ADVANCE

Field studies covering half a century and occasional observations over a period three times as long show that coastal Alaskan glaciers advanced within the last two hundred years to positions beyond those occupied at any time since the post-Wisconsin xerothermic period (Reid, 1892, p. 38; Klotz, 1899, p. 526; Blackwelder, 1907, pp. 420–421, 433; Gilbert, 1910, p. 103; Martin, 1913, pp. 128, 144–150; Tarr and Martin, 1914, pp. 35, 230; Cooper, 1931, pp. 88–89; 1937, pp. 43–47; 1939, p. 132; Mertie, 1931, pp. 122–123; Field, 1932, p. 371; 1937, p. 68; Wentworth and Ray, 1936, p. 932; Lawrence, 1950). A similar history is reported for some interior glaciers (McConnell, 1905, pp. 3A–4A; Capps,

1916, p. 79), and corresponding advances are known in widely distributed parts of the Northern Hemisphere (Ahlmann, 1935, pp. 203–206; 1941, p. 202; Finsterwalder, 1937, p. 103; Thorarinsson, 1940; 1943, pp. 49–50; R. J. Russell, 1941, p. 91; Matthes, 1942*a*, pp. 190–213; Flint, 1948, p. 159). In many places these advances are the most extensive of the post-Wisconsin interval (Kinzl, 1932, p. 396; Ahlmann, 1933, p. 195; 1948, pp. 72–73; Eythorsson, 1935, p. 136). Culminations of this modern ice flood have not been strictly synchronous in all localities or even within different parts of a single area, and in Alaska the point of farthest advance was reached by some glaciers one to two hundred years ago, while it is only now being attained by others (Field, 1937; Cooper, 1942*a*, pp. 4, 17–18). The number and variability of factors influencing the rate of glacier response to climatic or other changes make this understandable. However, culmination of the modern advance seems to have occurred almost everywhere within the last two to three hundred years, and the recent history of Wolf Creek glaciers conforms with this picture.

During the modern advance, Wolf Glacier fell 6 miles short of its canyon mouth, and no tributary glaciers entered the main valley below its snout. However, all south-wall tributaries above the snout joined the trunk glacier. These tributaries maintained their vigor for a time after shrinkage began in the trunk glacier, for they pushed forward slightly and built end moraines onto areas previously occupied by the trunk glacier. Delayed recession of tributary glaciers is also recorded on Jan Mayan Island (Flint, 1948, p. 125). Continued activity of Wolf Creek tributaries may have been due to a combination of location on north-facing slopes, steep floor gradients, and relatively large catchment areas. North Fork Glacier, a major Wisconsin tributary, fell 3 miles short of joining Wolf Glacier during the modern advance. Instead, the lateral margin of Wolf Glacier dammed North Fork Valley and formed a lake.

Terminal and lateral moraines bordering the existing glaciers are large in size and youthful in appearance (pls. 3, *B*; 4, *A*). They afford the best means of dating the modern advance, and in this respect moraines at the terminus of Wolf Glacier are most useful, for it was here that the trunk glacier extended below timber line. The meager growths of bushes and willow, alder, cottonwood, and spruce trees on these moraines contrast sharply with thick stands of mature white spruce on adjacent valley slopes. Trees on the moraines do not exceed an age of twenty years, but those on adjacent slopes approach three hundred years. Heavily forested alluvial cones constructed during the post-Wisconsin xerothermic recession are also easily distinguished from barren cones contemporaneous with the current recession (pl. 3, *A*). These relations show that the modern Wolf Glacier advanced into an area partly overgrown by a mature spruce forest. When more of the ice has wasted away, buried forests comparable to those of the Alaskan coast may be revealed.

Wolf Glacier did not recede from the terminal position of its modern advance in normal fashion but stagnated *in situ*. Thus much of the debris on which vegetation attempted to take root was unstable because of the melting of underlying ice. The debris content and melting rate of this ice (Sharp, 1949, p. 293) suggest that twenty to fifty years were required for development of an ablation mantle of sufficient thickness and stabil-

ity to permit establishment of the vegetation now growing on this material. A report of vegetation rooted in debris covering active ice (Lawrence, 1948, p. 28) favors the lower figure. An additional minimum of three or four to a maximum of perhaps twenty or thirty years (Tarr and Martin, 1914, p. 348; Cooper, 1931, pp. 65–66; 1939, p. 151; 1942*a*, p. 10; Kerr, 1936, p. 696; Wentworth and Ray, 1936, pp. 888, 926; Lawrence, 1950, p. 202) may have been required for the trees to get started, and some are now twenty years old. These vegetational relations suggest that the modern advance culminated between fifty and one hundred years ago. McConnell (1905, pp. 3A–4A, 10A) reports evidence of a glacier advance in Alsek Valley, 100 miles southeast, less than one hundred years ago, and Kerr (1936, p. 697) records an ice advance, starting about 1860, much farther south. It seems likely that the modern Wolf Creek advance corresponds to either or both the 1850 or 1890 *Hochstand* periods widely recognized in various parts of the world (Thorarinsson, 1940).

Cores were taken from white spruce trees along Wolf Creek, in the hope that the tree rings would reflect the harsher climatic conditions attending the modern advance and thus date that event. Two trees near the mouth of Wolf Creek experienced a decrease in radial growth between 1860 and 1870, with restriction continuing until the early 1920's. A faint suggestion of restricted growth during the late 1860's and early 1870's was also shown by two trees near the snout of Wolf Glacier. However, doubt is cast on the reliability of these examples by the fact that many other trees show no evidence of a corresponding retardation. Graphs of timber-line trees in the Alaska Range (Giddings, 1941, pp. 57–60) suggest a growth restriction from 1860–1870 onward. Giddings (1941, p. 75) also found a close relation between rings of timber-line trees in Alaska and variations in mean summer temperatures, probably because growth occurs largely in late June and early July in this environment. Hustich (1949, pp. 90–91) confirms the sensitivity to temperature change of trees in high latitudes. In view of this relation, the unreliable results obtained on Wolf Creek are all the more disappointing.

In places along North Fork and Wolf glaciers, the modern lateral moraine consists of a double ridge. The outer, slightly higher ridge is partly covered by willows and other low bushes, but the inner ridge is almost bare of vegetation and clearly somewhat younger. Terminal moraines of tributary glaciers 2, 7, 8, and 9 also show a bipartite arrangement consisting of an older outer area and a younger inner part. Kaskawulsh Glacier, 55 miles southeast of Wolf Creek, displays two modern end-moraine arcs, the outer of which has a growth of young spruce.[8] The modern advance in many other areas is also marked by a double morainic system (Ahlmann, 1941, pp. 199–202; 1948, pp. 72–73). These relations indicate a rejuvenation or a period of equilibrium within the recession following the modern advance. This is not surprising, in view of the present behavior of Wolf Creek glaciers, to be recounted shortly.

Advances of mountain glaciers may be of orogenic, seismic, or climatic origin. Orogenic uplift can produce an advance by increasing both total precipitation and the percentage that falls as snow, by increasing the area lying above the snow line, by bringing glacier snouts closer to the firn limit, and by reducing ablation. Earthquakes cause short-lived advances

[8] Personal communication, H. S. Bostock.

by shaking ice and snow down onto glaciers from surrounding slopes.

Tarr and Martin (1914, p. 196) suggest that violent earthquakes a century or more ago may have been responsible for the modern advance. Cooper (1937, p. 56) favors a climatic cause, arguing that earthquakes could not give the sustained increase in supply required for such a large and extensive advance. This objection appears sound because the ice and snow shaken down from mountain slopes must be replaced, and over an extended interval total nourishment is dependent chiefly on orographic and climatological conditions and not on earthquakes. Climatic control of the modern advance is also favored by the world-wide nature of this event and by the abundant and widespread evidence of a return to cool-moist conditions following the post-Wisconsin xerothermic period. Lawrence (1950, pp. 213–233) embraces climatic control and proposes to relate fluctuations of some coastal Alaskan glaciers during the last two centuries to cycles of sunspot activity. Orogenic uplift of the St. Elias Range during this period is a possibility not eliminated by any geological evidence known, and such uplift may have been a contributory factor.

In recapitulation, recession during the xerothermic interval was succeeded by an expansion and advance of Wolf Creek glaciers, which culminated fifty to a hundred years ago. Large raw lateral and terminal moraines and a trim line in a mature white spruce forest are the principal manifestations of this advance. Its culmination is dated by vegetational relations, by rate of ice melting and accumulation of ablation debris, and by analogy with the history of coastal Alaskan glaciers. Tree rings are disappointing as a means of dating the event, although they are faintly suggestive. Double moraines, possibly correlative with similar features in other areas, mark a pause or reactivation during shrinkage from the modern advance. A climatic rather than a seismic or orogenic cause is favored, although orogenic uplift is not eliminated as a possible contributory factor.

CURRENT BEHAVIOR OF GLACIERS

General statement.—In 1941 the Wolf Creek area afforded opportunity to study ice streams in advance, recession, and stagnation. The lower 9 miles of Wolf Glacier were stagnant, and the tip of North Fork Glacier appeared to be in a similar condition. Other glaciers were receding in normal fashion, and a few were advancing or expanding.

Stagnation.—Some tendency to regard the concept of glacier stagnation with mild skepticism demonstrates the need for firmly established examples of existing stagnant ice. The following features suggest stagnation in lower Wolf Glacier but are not infallible proof thereof: (1) heavy cover of superglacial debris of ablational origin (I. C. Russell, 1897, p. 153); (2) abundant superglacial ponds; (3) deeply incised superglacial streams (Flint, 1942*b*, pp. 120–121); (4) chaotic superglacial topography, consisting of short stream valleys, closed depressions, and debris-mantled knobs and ridges; (5) decayed condition of the ice as manifested by arches and englacial caverns, passages, and tunnels; (6) concave transverse profile; (7) great vertical shrinkage with little or no terminal recession; and (8) lack of crevasses.

All these features are displayed in the lower 9 miles of Wolf Glacier (pl. 4, *B*), and many are present in the lower 0.4 mile of North Fork Glacier. Stagnancy is strongly suggested in both instances, but confirmation is needed, for the only sure criterion of existing stagnant ice is in-

strumental measurement (Flint, 1942*b*, p. 121). A heavy cover of debris and a rough superglacial topography can occur on active ice (Ogilvie, 1904, pp. 725, 743), particularly if the debris has fallen from canyon walls (Speight, 1940, p. 134) or ablation is locally excessive (Mason, 1935, p. 25; Finsterwalder, 1937, p. 104; Klebelsberg, 1938, p. 40).

Photographs from fixed survey stations in 1935, 1939, and 1941 by Mr. and Mrs. Walter A. Wood give the required instrumental proof of Wolf Glacier stagnancy. Opposite point *5105* (fig. 2) on the south lateral moraine of the glacier 6 miles above its snout, the ice showed no perceptible down-valley movement between 1935 and 1941. Farther up-valley, opposite point *5564* (fig. 2), no movement occurred between 1935 and 1939, but the ice did move some tens of feet between 1939 and 1941. This later movement resulted from a rejuvenation to be discussed shortly. Proof of inactivity in lowermost Wolf Glacier over a longer period is afforded by alluvial cones built onto the glacier from tributary valleys, particularly along the north margin of the glacier, where the dark-brown cone debris contrasts with the white and gray ablation detritus. These cones have willows, ten to fifteen years old, growing on their surfaces, and it would seem that the cones can be no less than twenty to twenty-five years old. The lack of perceptible down-valley displacement of those parts of the cones resting on ice is significant. Admittedly, they lie on the glacier's margin, where movement would be least; but, if the ice were active, some evidence of displacement even at the margins within twenty to twenty-five years would be expected. Therefore, it is concluded that lower Wolf Glacier is truly stagnant and that the various criteria suggesting stagnation are locally valid. This also confirms stagnancy at the tip of North Fork Glacier.

The principal causes of stagnation in lower Wolf Glacier are: (1) decrease in nourishment or increase in ablation following culmination of the modern advance; (2) over-deepening of the valley near the bend during Wisconsin and earlier glaciations, possibly giving a reversed valley-floor gradient; (3) disjunction of the lower tributary glaciers.

Widespread glacier shrinkage and recession during the last century throughout Alaska and the Yukon is too well known to require further documentation. This recession presumably originated in a climatic amelioration, which is the fundamental cause of stagnation. However, other factors played a part, for climatic amelioration alone produces normal recession as readily as stagnation. Over-deepening of the valley floor at and below the bend is a likely contributory factor. Over-deepening is suggested by steepening of the surface slope on Wolf Glacier at this junction, and possible causes of this deepening are adequate. North Fork Glacier, a major tributary, formerly entered here, and over-deepening at such junctions is not uncommon. This is also the point at which the main valley becomes parallel with bedrock foliation and with the monocline or fault (Sharp, 1943, pp. 644–646) determining the lower course of Wolf Creek. Over-deepening might be sufficient to give the valley floor a reversed gradient.

The influence of debris on stagnation is not necessarily consistent. Ogilvie (1904, pp. 723–724, 742–743) feels that superglacial debris enables some glaciers to maintain themselves and even advance under conditions causing recession of debris-free glaciers. However, excessive melting of debris-free ice (Tarr, 1909, p. 62; Flint, 1942*b*, pp. 117–118)

may ultimately cause separation and stagnation of other masses of debris-covered ice. I. C. Russell (1895, p. 825) suggests that an overload of debris may reduce velocity and thus promote stagnancy. Streams of ice differ from most streams of water, in that nearly all the load is carried in suspension and the ice cannot easily get rid of this load when volume or gradient changes. Thus debris-laden ice must be driven across low-gradient reaches by pressure, either from behind or developed internally by differences in thickness. If these pressures diminish for any reason, such as decreased nourishment, the ice is likely to cease flowing and become stagnant. It is in this manner that debris is thought to have promoted stagnancy of Wolf Glacier.

Another factor favoring stagnation of lower Wolf Glacier was disjunction of four relatively large south-wall tributaries. Ice supplied by these glaciers helped the trunk glacier attain its farthest advance, and their disjunction deprived lower Wolf Glacier of nourishment which was exclusively its own. Shrinkage of the trunk glacier began before the tributaries receded, so disjunction was a contributory rather than a primary cause of stagnation.

Stagnation has been accompanied by 350–500 feet (pl. 4, *B*) of down-melting over much of the lower 9 miles of Wolf Glacier, but the terminus has receded only a few hundred yards. An estimated 400–500 feet of ice remain in the upper part of stagnant Wolf Glacier. Under present climatic conditions, but with progressively slower melting, owing to an increasing superglacial mantle, at least two centuries will be required to dispose of this ice. When it is gone, little evidence of stagnation will remain, for streams of meltwater sweeping the valley floor from wall to wall will quickly remove topographic irregularities in the glacial deposits and will spread a mantle of glacifluvial debris. Even the massive terminal moraine (pl. 3, *B*) may be removed, so that the subparallel lateral-moraine ridges, kame terraces, and marginal stream channels on the valley walls will be the only evidence that a progressively thinning, but not necessarily stagnant, glacier formerly occupied the valley.

Normal recession.—During normal recession a glacier maintains a distinct, but receding, terminus while ice within the body moves forward. Normal recession has occurred in the south-wall tributaries, glaciers 1–9 (fig. 2), between the Donjek and the bend in Wolf Creek. The snouts of these glaciers are low and largely free of debris (pl. 4, *A*). They show only slight dissection by superglacial streams and have none of the decayed aspects of stagnant ice. Photographs record a slight retreat and shrinkage in some between 1935 and 1941, but much greater thinning and recession over a longer period are indicated by abandoned lateral and end moraines. The spur cap west of glacier 9 also receded between 1939 and 1947.

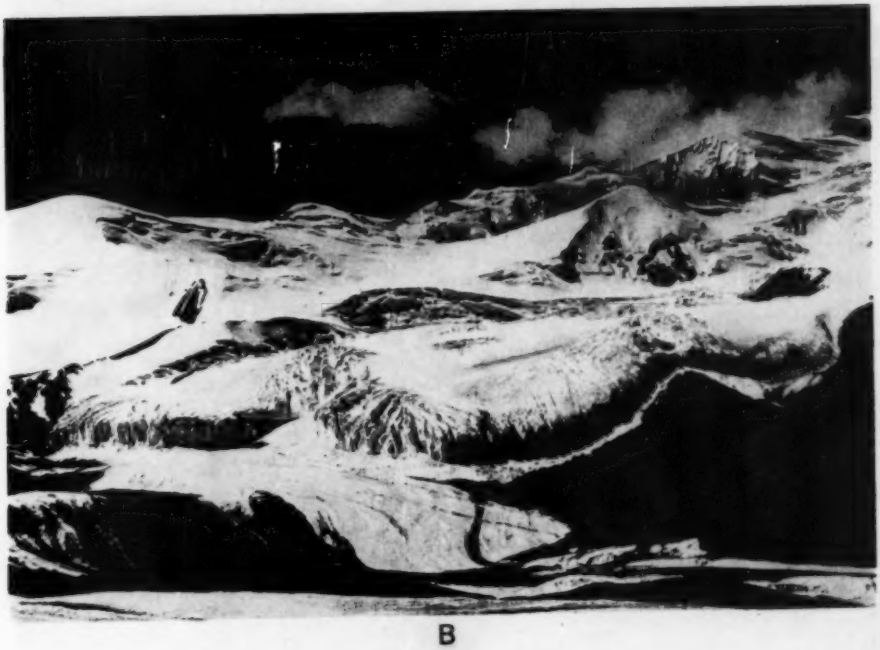
Gradient is probably the principal cause for the difference in behavior between the trunk and tributary glaciers. Each of the tributaries occupies a steep canyon, down which the ice streams con-

PLATE 5

A, View eastward across upper, active part of Wolf Glacier. Hanging snout of small glacier on far wall advanced at least 100 feet between 1936 and 1941. Photo by W. A. Wood, 1941.

B, Looking southwestward to the advancing snout of glacier 13 (fig. 2). Vertical ice cliff is 150–200 feet high and fully 1 mile long (1941).

A



B

Advancing glaciers

A

B

Expansion of tributary glacier

tinue to move, even though greatly thinned. Exposure, proximity to the firn limit, and relative size of catchment areas are possible secondary factors.

Advance and expansion.—Recorded observations of Wolf Creek glaciers cover the interval from 1935 to 1947, but during even this brief period some glaciers in the higher parts of the area have experienced a cycle of expansion and shrinkage. Rejuvenation was well under way in some ice streams by 1941, and its effects have continued beyond this date.

Snouts of the following glaciers were advancing during at least part of this period: (1) a small wall-sided glacier, protruding from a hanging valley on the east wall of upper Wolf Creek (pl. 5, *A*) about 2 miles south of glacier 11, advanced at least 100 feet between 1936 and 1941; (2) glacier 18, a small transection glacier on the north wall of Wolf Creek, advanced slightly between 1935 and 1941; and (3) glacier 13, draining from the east slope of Mount Wood, advanced eastward at least 200 feet between 1939 and 1941. As observed from the air in August, 1949, this glacier was advanced far beyond its terminal position of 1941.

These advancing glaciers have the following aspects in common: (1) all are relatively short; (2) they occupy positions of moderate elevation; (3) all have high gradients, and the lower parts of the first two rest on exceptionally steep slopes; (4) their snouts are nearly vertical cliffs, 150–200 feet high; (5) crevasses are abundant; and (6) the transverse surface profile is slightly convex. These glaciers differ among themselves, in that the first appears to be partly avalanche-fed, like some Himalayan glaciers (Finsterwalder, 1937, p. 69; Klebelsberg, 1939, p. 308). Avalanche feeding can be efficient and effective, and it may be one of the reasons for the advance of this particular glacier. The second advancing glacier is part of a larger ice stream flowing northward into the Cement Creek drainage, about which nothing is known. The third glacier is more normal, as it rises in a large névé and probably feeds from several small cirques, at present obscured by deep fillings of ice and firn. The snout of this glacier is a lobate, mile-long ice cliff, below which a talus of fallen ice blocks has accumulated (pl. 5, *B*). Transverse and longitudinal crevasses are abundant, and the ice is badly broken where it overrides a 75-foot gravel ridge. This ice stream is advancing onto the surface of another glacier and provides an excellent example of a superimposed ice stream in the making (Sharp, 1948, pp. 187–188).

Another aspect of the rejuvenation is the vertical and lateral expansion observed in two tributaries of upper Wolf Glacier. A camp site established in 1935 (Wood, 1936, p. 240) on the lateral moraine of a tributary glacier at the foot of Mount Steele was nearly buried by ice in 1941, owing to expansion of this tributary. Tributary glacier 10 also experienced a notable increase in thickness between 1935 and 1941. In 1935 easy access to its surface was attained from the lateral moraine at the junction with the trunk glacier, but in 1941 this path was barred by a wall of ice at least 50 feet high. Photographs suggest that this expansion was under way in 1939. It was

PLATE 6

A, North margin of glacier 10 (fig. 2) at junction with Wolf Glacier in 1935. Photo by W. A. Wood.
B, Same location as *A* in 1941. Increase in glacier thickness about 50 feet. Photo by F. H. Wood.

well advanced in 1941 (pl. 6), but by 1947 the glacier surface had returned to about the 1935 level. Convex transverse profiles and badly crevassed surfaces of other tributary ice streams in upper Wolf Creek suggest that they, too, have experienced similar expansions.

The date at which this renewed activity started is not known. It may have been under way prior to the first observations of 1935, although glacier 10 showed no particular signs of an expansion at that time. The results were faintly evident in 1939 and were unmistakable in 1941. The effects extended beyond 1941 in glacier 13 but had wholly disappeared in glacier 10 by 1947.

In view of the widespread deterioration and recession of glaciers in Alaska (Washburn, 1941, p. 220; Lawrence and Lawrence, 1949, p. 24), Canada, and throughout the world (Thorarinsson, 1940), it is difficult to believe that this renewed activity is anything but a minor interruption of the recession, shrinkage, and stagnation which set in on Wolf Creek fifty to a hundred years ago. Advance of a number of coastal Alaskan glaciers between 1935 and 1947[9] may have the same cause as the Wolf Creek rejuvenation. The large number of variable factors (Reid, 1895) influencing such a reactivation suggests that it need not be absolutely synchronous in all localities.

Seismic records (Gutenberg and Richter, 1949, pp. 144, 216) do not reveal any exceptional degree of earthquake activity in the environs of Wolf Creek prior to the recent expansion. The only possibility is an earthquake of magnitude 6 originating at 61° N., 140° W., on July 7, 1920. Judging from relations between glacier advance and the Yakutat Bay shock of 1899 (Tarr and Martin, 1914, pp. 172, 180–185), the 1920 quake is too early to be related to the Wolf Creek rejuvenation, and its energy was considerably less than the Yakutat quake with a magnitude of 8.25–8.5.

Meteorological records are more promising, although better data from nearer stations would be desirable. Kennecott, Alaska, 90 miles west of Wolf Creek, is the only station with reasonably comparable topographic and climatic environment and with records of sufficient length and detail to be of use. In respect to climate, glacier behavior is affected chiefly by total snowfall and the intensity and duration of the ablation season. Because practically all precipitation in the gathering areas of Wolf Creek is snow, variations in annual precipitation give a measure of changing nourishment. Seasonal snowfall, the amount occurring between July 1 and June 30 of succeeding years, confirms the variation of annual precipitation in most cases. The only measure of changes in ablation intensity given by the records is that indicated by departures from mean temperatures during the ablation season, here arbitrarily taken as May to September, inclusive. Variations in length of the ablation period may be more significant (Ahlmann, 1948, p. 77) but cannot be determined from the records.

As plotted (fig. 3), these data indicate that the interval 1929–1939 was more favorable for glaciers than were the preceding or succeeding periods. The years 1929, 1932, and 1939 were especially favorable, but the 1930's as a whole were distinguished by increased nourishment and reduced ablation. These curves (fig. 3) support the conclusion that the recent expansion of Wolf Creek glaciers is of climatological origin and, further, suggest that the initial impetus started about 1929.

[9] Unpublished manuscript of W. O. Field, quoted with permission.

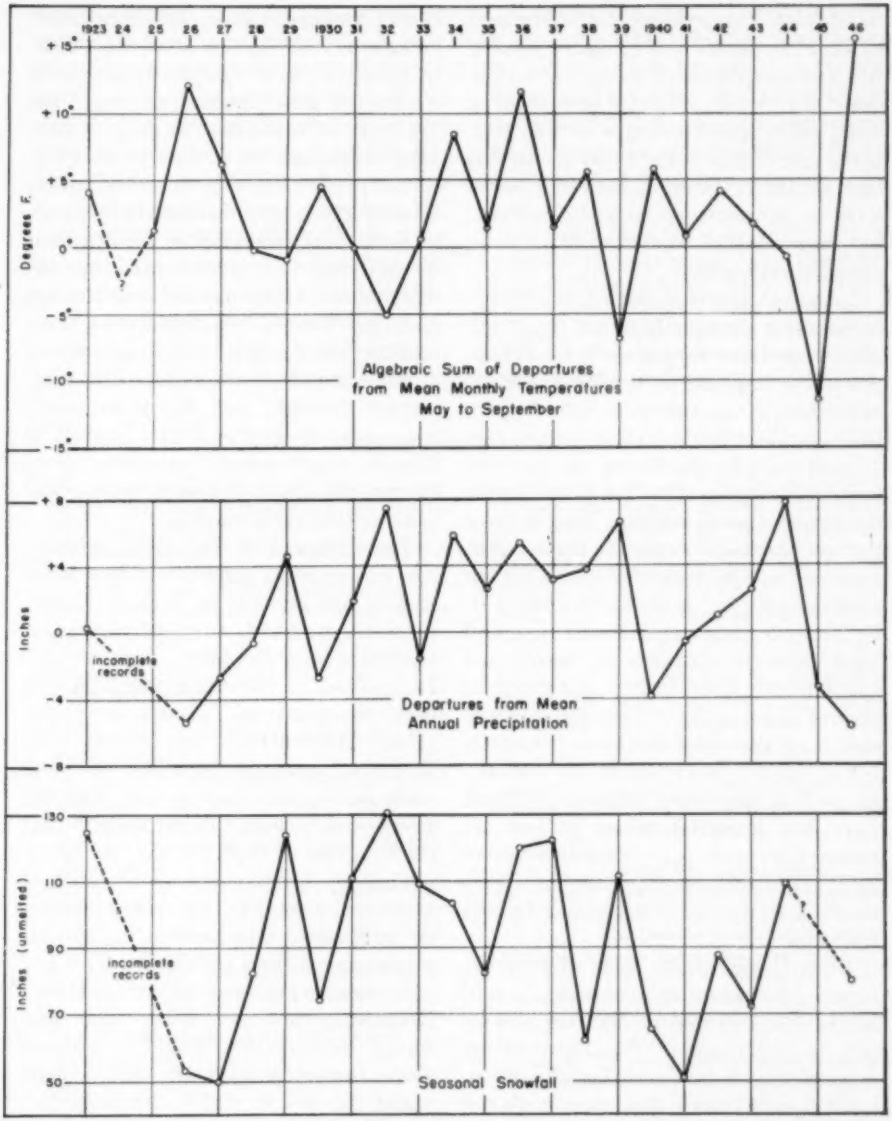


FIG. 3.—Plots of selected climatic data at Kennecott, Alaska, 61°29′ N., 142°47′ W., elevation 2,003 feet

A medial moraine on upper Wolf Glacier displays two prominent kinks formed by rapid advances of a tributary glacier. Air photographs taken in 1936 and 1941 show the lower kink to have moved down-valley about 0.75 mile in five years. If the rate of flow in the trunk glacier has been constant, the upper kink may be related to the rejuvenation just described, but the lower kink would be related to an earlier reactivation.

Increased activity within the tributaries must eventually affect the trunk glacier, and one wonders what will happen in the stagnant part of Wolf Glacier. Something of an answer is furnished by photographs taken from fixed survey stations in 1947 by the Woods. In 1941 the uppermost stagnant part of Wolf Glacier developed signs of activity. Two or three narrow crevasses formed in the ice that summer, and photographs from a survey station (*5564*, fig. 2) showed a down-valley flow of a few feet between 1939 and 1941. Between 1941 and 1947 movement opposite the same station amounted to several hundred feet.[10] Opposite a lower station, about 6 miles above the snout (*5105*, fig. 2), Wolf Glacier showed absolutely no movement between 1935 and 1941, but it shifted about 50 feet between 1941 and 1947. This last movement is probably an expression of the renewed activity recognized earlier farther up-valley.

Even though upper Wolf Glacier has experienced recent rejuvenation, it need not be assumed that all the stagnant ice will be reactivated. The rejuvenation may die out before reaching the snout, for it is well known that many a glacier moves more rapidly in its upper than in its lower part (Thorarinsson, 1939, p. 202; Matthes, 1946, pp. 223–224). If other factors, such as valley size and shape, remain constant, this difference in forward velocity can be attributed largely to surfaceward movement of ice by obstructed flow (Demorest, 1943, pp. 365–373) or rotational slipping (Lewis, 1949) to replace the ice lost by ablation. Above the firn limit the vector of flow in a valley glacier may be essentially parallel with its bed, but below the firn limit flowage has two components, one directed down-valley parallel with the bed and one directed surfaceward at some undetermined angle. As the amount of ablation increases, the surfaceward component increases and the down-valley component diminishes. Hence lower Wolf Glacier may remain stagnant, even though the upper section is moving and experiencing rejuvenation.

The existence of stagnating, advancing, and receding glaciers within a small area is not unusual in Alaska (Capps, 1910, p. 56; Field, 1932, p. 385; 1942; Lawrence and Lawrence, 1949, p. 25). Discussions of this relationship by Gilbert (1910, p. 109), Cooper (1937, pp. 59–60), Field (1937, pp. 68, 74, 81), Matthes (1942*b*, pp. 386, 389, 390), and Ahlmann (1940*a*; 1940*b*, p. 125; 1948, pp. 50–55, 63), among others, suggest that the behavior at Wolf Creek could be explained by a minor rise of the zone of maximum snowfall. This would produce an increase of nourishment on glaciers originating above a certain elevation and a decrease on glaciers originating at lower elevations, thus permitting their continued deterioration while ice streams more favorably situated were rejuvenated.

In summary, following the modern advance, shrinkage, recession, and stagnation have ruled. Wolf Glacier is shown to be stagnant in its lower 9 miles by observations from established survey sta-

[10] Exact measurements will not be possible until Mr. Wood completes photogrammetrical plotting.

tions covering a period of twelve years, and this stagnancy is confirmed and extended in time by geological features. Stagnation is attributed to climatic amelioration, to over-deepening of the valley floor, and to disjunction of the lower tributaries. The trunk glacier has melted down *in situ* 350–500 feet with terminal recession of only a few hundred yards, while steep-gradient tributary ice streams have shrunk and receded in normal fashion. This deterioration has probably been interrupted repeatedly by reactivation of favorably situated glaciers, and such a rejuvenation began most recently in the late 1930's. The uppermost stagnant section of Wolf Glacier has been affected by this reactivation, which reached a peak in the early 1940's and was on the wane by the late 1940's in most glaciers. Meteorological and seismic records suggest a climatic rather than a seismic cause for the rejuvenation.

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GEOMETRY OF SHEARING STRESS AND RELATION TO FAULTING[1]

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ABSTRACT

The distributions of intensity and orientation of maximum shearing stress in typical stress systems are plotted on stereographic projections in order to show the three-dimensional relationships. Mathematical expressions of these relationships as well as graphical methods of evaluation are given. Relationships of shearing stress to orientation of fault planes and orientation of net slip of faults are suggested. Methods of studying the relationships of faults and shearing stress are described.

INTRODUCTION

The solid geometry of shearing stress carries important implications pertaining to faulting and structural deformation, yet it has received only slight attention by geologists. Schmidt (1938), Sander (1940), Anderson (1948), and others have utilized the principle in interpretations. Schmidt's paper is an excellent treatment of the geometry of shearing stress and has served as corroboration of part of the present study. The problem of stress analysis in three dimensions has been a source of many discrepancies and incomplete understanding. The stereographic projection is used here in an attempt to illustrate the three-dimensional aspect of the problem.

SHEARING-STRESS INTENSITY

The total stress on any plane in a stress system can be broken into two components, one normal to the plane and the other parallel to the plane. These components are known as "normal stress" and "shearing stress," respectively.

The intensity of maximum shearing stress to which any plane in a homogeneous elastic body under stress is subjected can be expressed by the formula

$$S^2 = n_1^2 \cos a^2 + n_2^2 \cos b^2 + n_3 \cos c^2 - (n_1 \cos a^2 + n_2 \cos b^2 + n_3 \cos c^2)^2 ,$$

where S = shearing stress; n_1, n_2, and n_3 are the three principal stresses always at right angles with + values representing compression and − values representing tension; and a, b, and c are the angles from n_1, n_2, and n_3 axes, respectively, to the plane's normal. The derivation of this formula can be found in publications by Nadai (1931, p. 42), Bucher (1921), and others.

In order to picture the variation of intensity of shearing stress with various orientations of planes in a stress system, the stereographic projection has been employed. By this projection method, which represents a hemisphere plotted on a circle (Ford, 1932; Fisher, 1941; Bucher, 1944), the planes can be plotted as points in a circle; the points represent the intersection of the planes' normals with the hemisphere's surface or, stated another way, the points of tangency of the planes and sphere. In all the stereographic diagrams the lower hemisphere of the unit sphere is pictured. The intensity of shearing stress on a particular plane is plotted at the point representing the plane. The various intensities can then be contoured to show a complete diagram of the variation of shearing-stress intensity (fig. 1).

If the intensity on numerous planes in a stress system is to be determined, the following graphic solution using Mohr's stress plane is more rapid than solution

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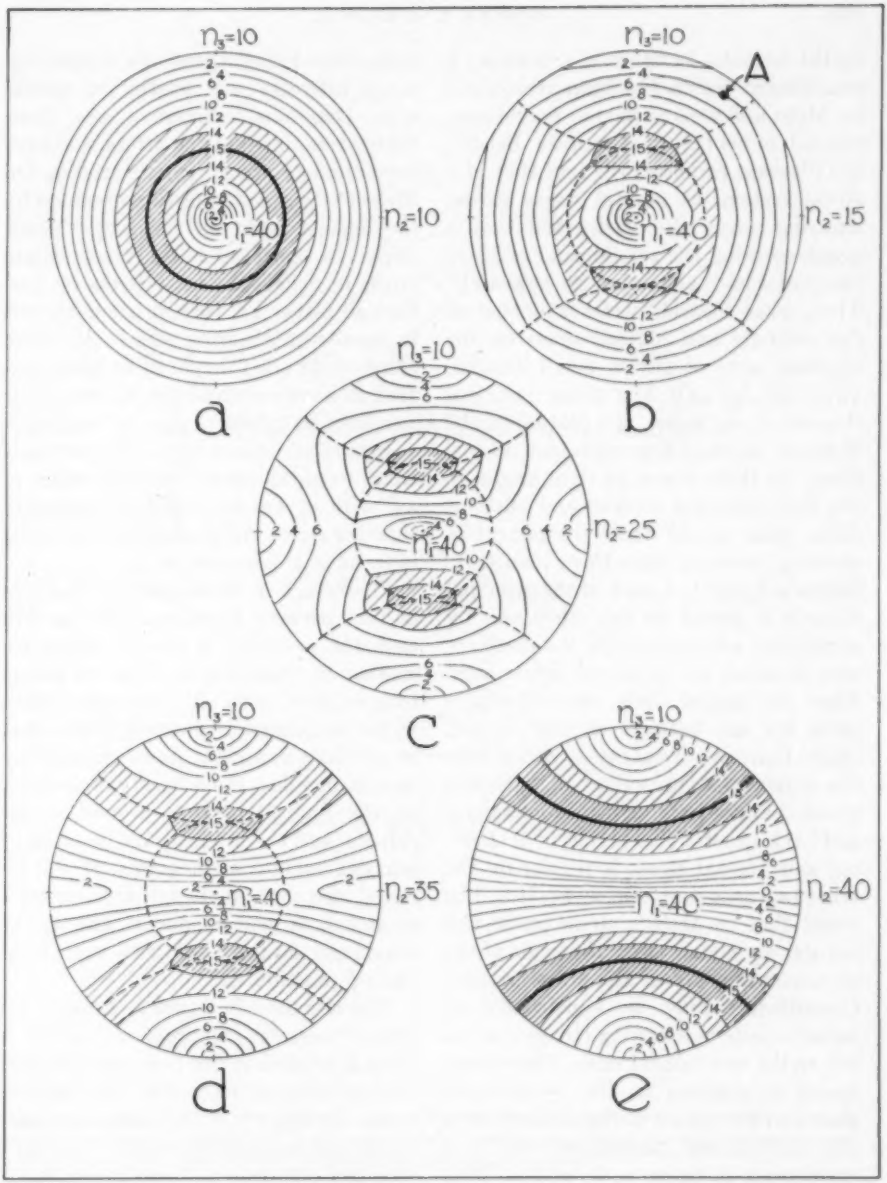


FIG. 1.—Intensities of shearing stress plotted on stereographic nets. N_1, N_2, and N_3 are principal axes. Intensity at any point represents shearing stress on a plan whose pole is that point (or a plane tangent to the sphere at that point). For example: Point *A* in figure *b* represents a plane striking N. 54° W. and dipping 84° SW., which is subjected to a shearing stress of 4 (lb/in², or whatever units are used) in this particular stress system. Dashed lines in 1, *b*, *c*, and *d* represent positions of cones around N_1 and N_3. See text for explanation.

by the formula. In figure 2, *a*, is shown a relationship which has been recognized by Mohr and used as part of the demonstration of his theory of rupture. Briefly, the diagram expresses the fact that in a stress system, as normal stress varies, shearing stress also varies and that a graph showing the relationship of these two variables is always an arc of a circle. Thus, when shearing stress is plotted on the ordinate and normal stress on the abscissa, arcs of circles result (Nadai, 1931, pp. 43–44). The three principal stresses, n_1, n_2, and n_3, are plotted on the abscissa, as they also represent normal stress for three planes at right angles to the three principal stresses and, furthermore, there would be no component of shearing stress on these three planes. As shown in figure 2, *a*, each of the principal stresses is joined to the other two by semicircles which represent the three 90° arcs between the principal stress axes. Thus the largest circle (dotted) represents the arc between n_1 and n_3 and shows that, as normal stress varies from the value of n_1 to the value of n_3, shearing stress changes from zero to a maximum and back to zero. The variation of shearing and normal stress is similar on the other two arcs n_1–n_2 and n_2–n_3. It will be noted that in Mohr's stress plane any circular arc equals twice the angle of the corresponding arc of the stress system. Co-ordinates may be constructed in Mohr's circle by drawing circles concentric to the two smaller ones. They correspond in position to the co-ordinates shown in the octant of the stress system (fig. 2, *b*); dotted, dashed, and solid arcs correspond in figure 2, *a*, and *b*. With Mohr's stress plane and circles constructed, values of normal and shearing stress can be read off the abscissa and ordinate axes for any plane in the stress system.

Several features of the resulting patterns formed by the contours of shearing-stress intensity are worthy of special note. Diagrams in figure 1, *a*–*e*, show that maximum shearing stress is always present on planes 45° from n_1 and n_3. On Mohr's stress plane this is represented by the highest point on the largest semicircle. In figure 1, *a*, the intermediate stress n_2 equals the least stress n_3, and thus all planes 45° from n_1 are subjected to maximum shearing stress. All these planes might be thought of as being tangent to a cone around the n_1 axis. This cone can be called "a cone of maxima."

In similar manner (fig. 1, *e*), when n_2 is equal to n_1, all planes forming angles of 45° with n_3 are subjected to maximum shearing stress. All these planes would be tangent to a cone around n_3.

Figure 1, *b*–*d*, shows patterns for gradations between figure 1, *a* and *e*, and in each the positions of the 45° cones are marked by dashed lines. When n_2 differs from either n_1 or n_3, only one plane is subjected to maximum shearing stress, that at 45° from n_1 and n_3. As n_2 varies away from n_1 in value, the intensity of shearing on the cone of maxima around n_1 decreases, and the intensity on the cone of maxima around n_3 increases. It will be noted also that on the 90° arcs between n_1 and n_2, n_2 and n_3, and n_1 and n_3 the maximum shearing stress on each is at the 45° position.

The situation in figure 1, *a*, might be called "uniaxial compression," where a force is applied in one principal axis and the confining forces on the other two are equal. In figure 1, *e*, the situation might be likened to uniaxial tension. The intensity and orientation of maximum shearing stress is governed only by the relative values of n_1, n_2, and n_3. Thus, even if n_3 represents compression, if it is algebraically less than n_1 and n_2, the effect on shearing stress would be the same as if it were an axis of tension.

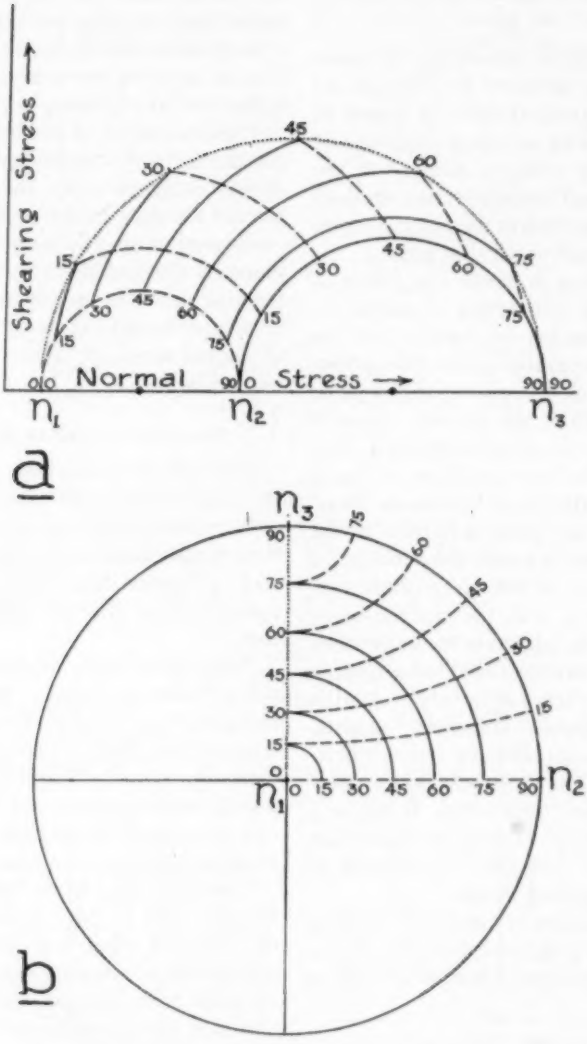


FIG. 2.—*a*, Mohr's stress plane, showing relation between shearing stress intensity and normal stress intensity in octant of a sphere. *b*, Octant of sphere plotted on stereographic net, showing relation of octant to Mohr's stress plane; dotted, dashed, and solid arcs correspond in *a* and *b*.

ORIENTATION OF MAXIMUM SHEARING STRESS

The variation of orientation of maximum shearing stress on different planes in different stress systems is shown in figure 3. In this figure it is perhaps easiest to picture any plane as tangent to the hemisphere, and the orientation of maximum shearing stress in the plane is represented by the arrow at that point.

In the pattern in figure 3, *a*, where n_1 equals n_3, the orientation of maximum shearing stress on any plane can be thought of as parallel to the line of tangency between the plane and a cone around n_1. Thus the arrows all point down, away from n_1, representing a "dip-slip" orientation on any plane. In figure 3, *e*, the orientation of maximum shearing stress on any plane is parallel to the line of tangency between the plane and a cone around n_3. In the intermediate situations, figure 3, *b–d*, the orientation of maximum shearing stress varies between the two orientations indicated above. In figure 3, *b–d*, planes with very steep dips would have almost "strike-slip" orientation of maximum shearing stress, whereas planes of low dip would have essentially "dip-slip" orientation. In figure 3, *b*, only the planes of steepest dip deviate greatly from "dip-slip" orientation of maximum shearing stress.

The orientation of maximum shearing stress on any plane in a given stress system may be expressed mathematically as follows:[2]

$$\cos d = \frac{\cos a}{S}(n_1 - N),$$

$$\cos e = \frac{\cos b}{S}(n_2 - N),$$

$$\cos f = \frac{\cos c}{S}(n_3 - N)$$

where n_1, n_2, and n_3 are principal stresses; *a*, *b*, and *c* are angles from the principal axes to the plane's normal; *d*, *e*, and *f* are angles from the principal axes to the line of maximum shearing stress in the plane; S is the shearing-stress intensity; and N is the normal stress intensity.

The orientation of maximum shearing stress may be determined graphically, as shown in figure 4. In this diagram is plotted the distribution of normal stress (values taken directly from Mohr's stress plane as illustrated in fig. 2). Shearing stress as shown at sample points *A* and *B* is oriented at right angles to the contours of normal stress, or "down-gradient" of normal stress.

RELATION TO SHEAR RUPTURE

It is difficult to correlate conditions in the elastic state with conditions at and after rupture, although it is the conditions in the elastic state that precede and lead to rupture. Any theory of rupture is confronted by this difficulty of correlation.

The present study of shearing stress is not a theory of rupture, for all that is concerned is a resolution of principal stresses into that component known as "shearing stress." However, a comparison of shearing stress and shearing rupture provides a useful basis for studying shearing rupture.

Experimental work described by Griggs (1936, p. 555), Nadai (1931, pp. 62, 65), and others has shown that the orientation of shearing rupture does not coincide with the planes of maximum shearing stress; rather, it develops on planes which form angles less than 45° with the axis of greatest compressive stress. Mohr's theory (Nadai, 1931, p. 61) includes both normal and shearing

[2] The mathematical expression here given was kindly prepared by Dr. Bernard Fried, of the Department of Mechanical Engineering at the State College of Washington.

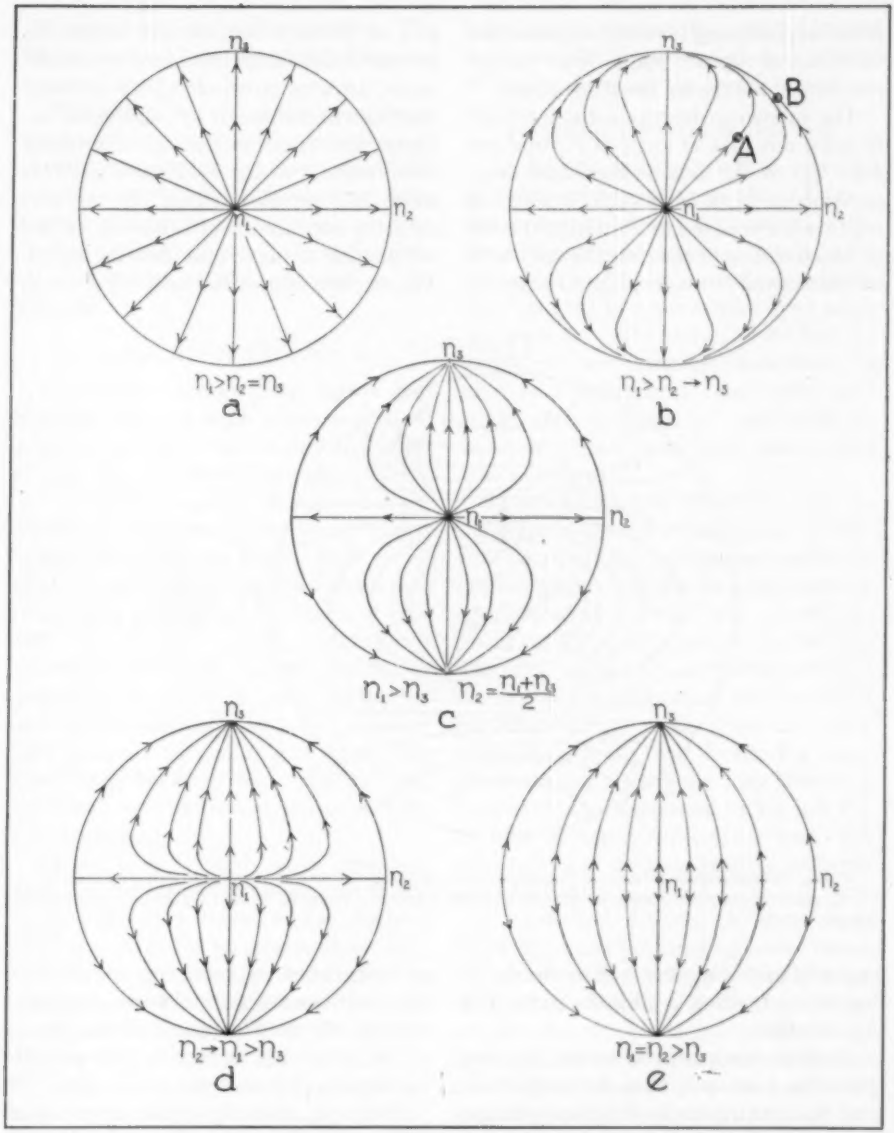


FIG. 3.—Orientation of maximum shearing stress plotted on stereographic nets. N_1, N_2, and N_3 are principal stresses and correspond approximately to values in figure 1. For example: Point *A* in figure *b* represents a plane striking N. 45° W. and dipping 65° SW. On this plane the orientation of maximum shearing stress is parallel to dip. Point *B* represents a vertical plane striking N. 45° W. On this plane the orientation of maximum shearing stress is parallel to strike.

stress as governing factors to explain this variation of rupture planes from the 45° position of maximum shearing stress.

The following description is intended to point out that an angle of rupture less than 45° to the axis of maximum compression is quite expectable if shearing rupture is compared to friction problems, in which sliding or shearing depends both on the normal stress, tending to push the opposite parts together, and on the shearing stress, tending to slide the parts past one another.

Normal compressive stress on any plane in a stress system increases from zero to a maximum as the plane changes from an orientation parallel to the axis of maximum compression to an orientation normal to that axis. Thus less tangential stress (shearing stress) is required to cause shearing when the plane approaches an orientation parallel to the axis of greatest compressive stress. As normal stress varies from zero to a maximum, shearing stress changes from zero, reaches a maximum at 45°, and again becomes zero at 90° to the axis of greatest compression (see fig. 2). If normal stress were constant throughout the 90° arc, shearing rupture should develop at the orientation of maximum shearing stress. The tendency is for the body to shear at an orientation representing a compromise between low normal stress and high shearing stress. This would always be at 45° or less with respect to the axis of maximum compression.

Although shearing stress alone does not govern the angle of rupture, it is a basic consideration. The patterns shown in figure 1 represent only shearing-stress intensities, but the patterns of "potential rupture" in a homogeneous body of infinite dimensions should be very simi-

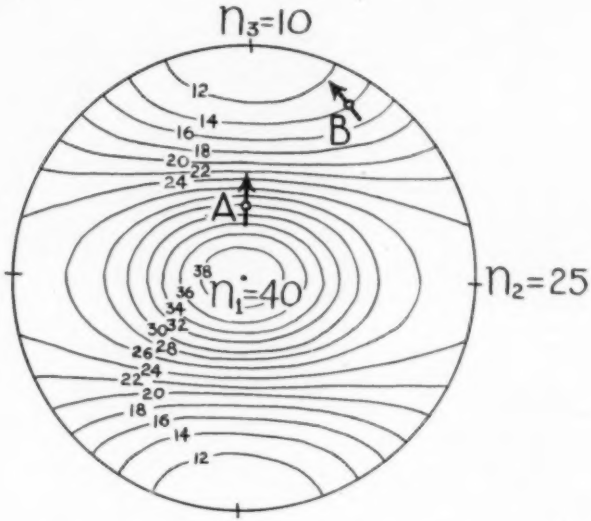


FIG. 4.—Stereographic projection of normal stress, showing direction of maximum shearing stress to be "down gradient" of normal stress as at sample points *A* and *B*. Points N_1, N_2, and N_3 are principal normal stresses.

lar, differing only by having the zones of maxima at angles slightly nearer n_1. The variation would be dependent upon the material involved.

The correlation of orientation of maximum shearing stress with orientation of shearing motion in rupture is essentially a direct correlation. It should vary from perfect correlation at the instant of rupture and should diverge only as the elastic continuity of the material is destroyed.

RELATION TO FAULTING

Correlation of shearing stress and shearing rupture with faults in nature adds innumerable variables, which complicate the problem of analysis. Indeed, the variations possible are somewhat bewildering. Following are some major complicating factors. First, the shape of the tectonic blocks affects the distribution of shearing stress and orientation of rupture. Second, the strength anisotropism of rocks is of infinite variety. Third, the sequence of shifting orientations of stresses causing deformation is a factor very difficult to evaluate. Fourth, the distinction between shear rupture and tensional rupture in some cases is difficult to make.

In the present study it is intended, first, to indicate the manner in which faults will follow preferred orientations with respect to the stresses and, second, to indicate the relationship of net slip orientation to the orientation of the fault plane and the stress system. To do this with some degree of simplicity, three of the above-mentioned complicating variables are considered absent, and only the factor of strength anisotropism is retained. It would seem, upon considering the regularity of some fault systems, that this assumed degree of simplicity is not too uncommon in nature. In the great majority of cases a variety of complicating factors is present; but, to understand such complex situations, it is necessary first to understand the simpler cases.

PREFERRED ORIENTATIONS OF FAULTS

Faults will essentially follow a pattern of distribution similar to that of "rupture-potential" maxima discussed in the preceding section. In homogeneous rocks, faults will tend to concentrate at orientations tangent to a cone, with apex angle less than 90° (45° radius), which has the axis of greatest compressive stress as its axis; or tangent to a cone, with apex angle greater than 90° (45° radius), which has the axis of least compressive stress as its axis.

Strength anisotropism of the rock can outweigh in effect the distribution of rupture potential in homogeneous rocks described above, and the resulting pattern of rupture can be drastically altered. An orientation of great weakness in the rock may well become a fault plane, although that particular orientation is subjected to far less shearing stress than are other orientations in the rock. In effect, a plane of almost any orientation may become a fault in nonhomogeneous rocks, but the over-all grouping of orientations will tend to follow the two conelike patterns described above.

An example follows to show how faults, apparently belonging to one stress system, may be correlated on the basis of orientation. Figure 5 shows by stereographic diagram how a group of faults in the Wallace formation of northern Idaho fall roughly tangent to a cone with an apex angle slightly greater than 90° (or radius of 45°). N_3 is located by trial of various circles to find one which is most nearly tangent to all the faults. The angular center of this circle is then interpreted as being a principal stress axis—in

this case the axis of least compressive stress because of the reverse nature of all faults.

The faults used in the example were observed in a mine tunnel where exposures were excellent and orientations of fault planes and relative displacements could be determined with a good degree of accuracy. Displacements on the faults range between 6 inches and 2 feet, and all are within a single large tectonic block measuring thousands of feet on a side. The rocks are massive, banded, limey argillites, which seem to have behaved as relatively homogeneous material. Bedding planes have not acted as planes of weakness but were very useful in determining the relative offset on the faults.

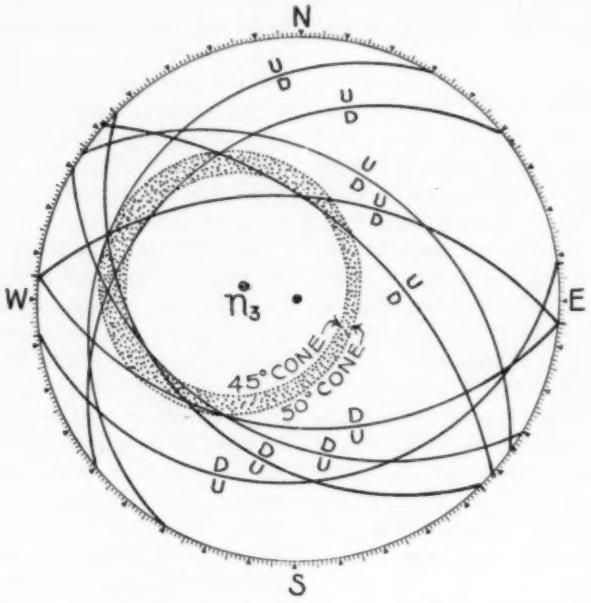


FIG. 5.—Stereographic projection of faults (plotted as great circles) in Wallace formation near Wallace, Idaho, showing possible relation to cones around axis of least compressive stress.

ORIENTATION OF NET SLIP

Orientation of net slip on faults can be correlated almost directly with orientation of maximum shearing stress (fig. 3) as long as any continuity is maintained to the stress system after first rupture. The solid geometry of this relationship introduces complexities which are suggested by the following examples. Methods for dealing with certain aspects of the geometry are suggested.

Figure 6 shows by stereographic representation and map representation how, on three hypothetical faults, all striking the same way but of different dips, the net-slip orientation (heavy arrows) varies in three simple stress systems. This interpretation is taken directly from the pat-

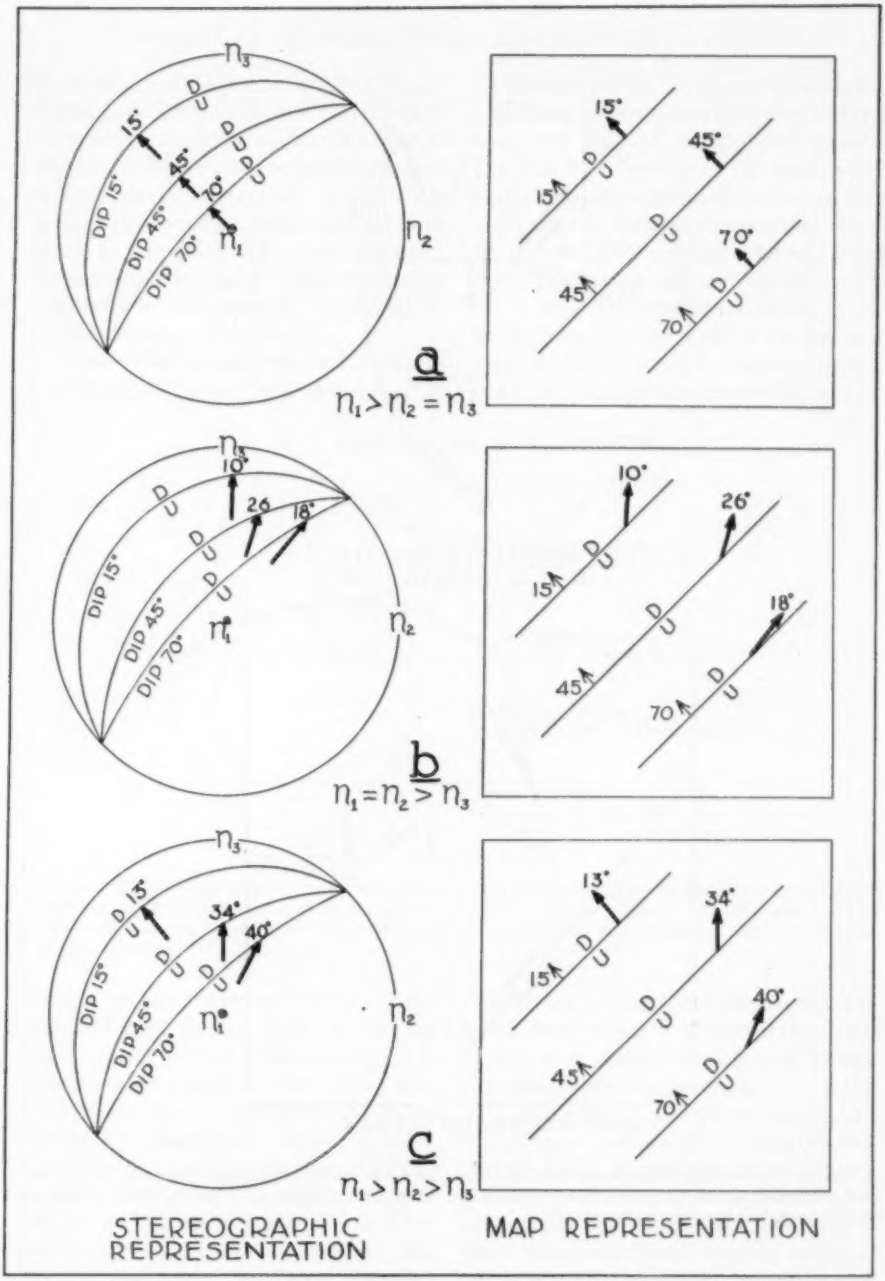
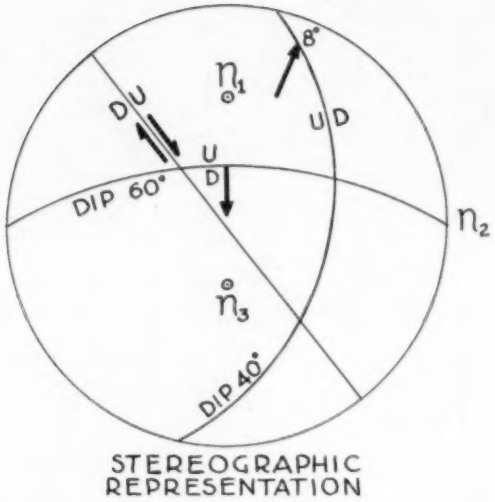
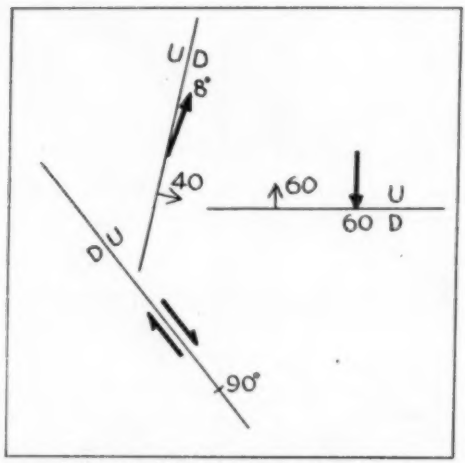


FIG. 6.—Orientation of maximum shearing stress (*heavy arrows*) on three sample planes, in three stress systems shown in stereographic representation (*left*) and expressed as orientation of net slip on faults (*right*). N_1 = axis of greatest compressive stress, N_2 = axis of intermediate compressive stress, N_3 = axis of least compressive stress.



STEREOGRAPHIC REPRESENTATION



MAP REPRESENTATION

FIG. 7.—Orientation of maximum shearing stress (*heavy arrows*) on three simple planes in sample uniaxial compression, where axis of greatest compressive stress (N_1) plunges 30° to north, shown by stereographic projection and map representaton.

terns of orientation of maximum shearing stress shown in figure 3 and represents a direct correlation of net slip with maximum shearing stress for the purpose of illustration. In figure 7 a strike-slip fault, a reverse fault, and a normal fault result in a single uniaxial stress system, illustrating the complexity of net-slip orientations that can be produced in simple uniaxial stress systems.

Where orientation of the stress system is as shown in figure 3, the orientation of indicated previously, the orientations of maximum shearing stress in uniaxial tension and uniaxial compression parallel the line of tangency of the fault plane and a cone around either the axis of least or the axis of greatest compression. Thus, by constructing a circle (representing a cone) around the axis considered (see fig. 8), so that the circle is tangent to the fault plane (represented by the arc of a great circle), a line from the point of tangency to the sphere center represents the

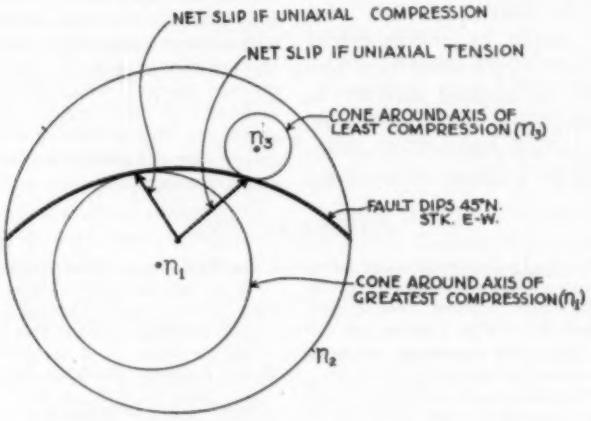

NET SLIP IF UNIAXIAL COMPRESSION
NET SLIP IF UNIAXIAL TENSION
CONE AROUND AXIS OF LEAST COMPRESSION (N_3)
N_3
FAULT DIPS 45°N. STK. E-W.
N_1
CONE AROUND AXIS OF GREATEST COMPRESSION (N_1)
N_2

FIG. 8.—Graphical determination of orientation of maximum shearing stress in simple tension and simple compression with any orientation of N_1, N_2, and N_3. These two orientations serve as limits between which lie all possible orientations of maximum shearing stress on this plane with this stress system orientation, regardless of values of N_1, N_2, and N_3.

net slip on any plane can be readily determined from the diagrams. Where the stress system is tilted, this correlation is in some cases difficult to see without first rotating all planes and points into the orientation diagramed. It is in some cases useful to construct the resolved shearing-stress orientations for uniaxial tension and uniaxial compression. This provides two limits between which fall the orientations of maximum shearing stress for all cases where the values of the three principal stresses are different. As orientation of trend and plunge of maximum shearing stress. With the two limits determined, an approximation of the net-slip orientation can be made.

If a complete picture of fault-plane orientations and net-slip orientations on several faults is available, it should be possible to determine with some degree of certainty the orientation and nature of the stress system producing the faults. If partial data are available, it may be possible to use this information in a limited prediction of the unknown factors. For

example, if the orientations of several fault planes are known and it is believed that they are related to the same stress system, the orientations and relative movement of net slip on the various faults should have a definite relationship to one another and to the fault planes.

LIMITATIONS

Although it is believed that the geometry of shearing stress described in this paper supplies an extremely useful basis for the interpretation of some fault systems and the solution of some fault problems, it should be re-emphasized that the concept in the limited form here presented can be applied directly to faults in relatively few and special cases. It is felt that the importance lies in establishing a basis for a better three-dimensional concept of the elementary problem. The application of these principles to actual field problems will require the accounting of perhaps several more variables, and, although this poses very serious difficulties, it does not lessen the need for an adequate, three-dimensional concept of stress as a foundation upon which the other variables can be stacked.

ACKNOWLEDGMENTS.—Deep appreciation is expressed to Dr. Bernard Fried for assistance in developing mathematical expressions as noted and for reviewing parts of the paper. In the early stages of the study, considerable help and guidance were obtained from Eleanora B. Knopf, and criticism of some of the ideas was kindly given by David T. Griggs. Zdenek Jizba helped materially in clarifying several points in the study, and Thomas Cheney and Charles Hummel performed a group of tedious calculations to check certain results.

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A PRELIMINARY INVESTIGATION OF THE RELATIVE ABUNDANCE OF THE CARBON ISOTOPES IN SWEDISH ROCKS[1]

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ABSTRACT

The ratio C^{12}/C^{13} has been determined for eighteen samples of graphite and twenty-three samples of limestone, all except one from Sweden. The measurements confirm the results obtained by earlier investigators.

INTRODUCTION

This investigation is intended to unravel the distribution of C^{12}/C^{13} in carbonaceous material of various compositions and different geological modes of occurrence and also from various epochs in the Swedish rock formations. The principal stress has been placed on pre-Cambrian carbon, whereas the work on material from younger formations is a completion of earlier work on this subject and ties up directly with the figures published in other papers (Nier and Gulbransen, 1939; Murphey and Nier, 1941; West, 1945; and Rankama, 1948*b*). However, the investigation is only a preliminary orientation in the wider study of the isotopes of carbon and their variations in the realm of geological systems.

The following points deserve continued study and closer observation, and investigation of them is now, in fact, under way (see following paper by Wickman and co-workers).

1. Further investigation of the relationship between carbon in graphite and carbon in limestone
2. An investigation of the carbonatic rocks (tied up with the alkaline rocks at Alnö); also an orientation in the study of the different carbonate minerals
3. The variations, both horizontal and vertical, occurring within the Cambro-Silurian limestones
4. Analogous variations within aluminous shales
5. The eventual influence which metamorphism may have upon the distribution of carbon isotopes
6. The distribution of the isotopes in atmospheric carbon dioxide

During the course of the present investigation, Rankama (1948*a*) published the results of his examination of the graphite-bearing rocks in Finland. Rankama's analyses were carried out with the same mass spectrometer which Nier and his co-workers used in their later work.

The author had the extraordinary good fortune to have had the requisite analyses performed by Dr. von Ubisch, of the Chemistry Department of the Karolinska Institutet. The C^{12}/C^{13} ratio is obtained from the relative maxima for the masses 44 and 45. The values are corrected for the contribution of $C^{12}O^{16}O^{17}$ to the peak for mass 45. At this correction, the ratio O^{17}/O^{16} is assumed to be 1/2,500.

Five determinations were made on every sample. Before and after each of the series of determinations, one on a standard was made, the conditions being held constant as nearly as possible. The results given in the tables are thus the

[1] Paper no. 1 in a series devoted to the application of isotope ratios to geological problems. Manuscript received July 18, 1950.

averages of five analyses which were not permitted to vary too much.

Dr. von Ubisch has given (in a letter to the author) the following information about the accuracy obtained with his mass spectrometer:

> A mass spectrometer discriminates slightly between species which are somewhat different in molecular, or atomic, weight but which still are chemically identical [Wilson, Nier, and Riemann, 1946]. Experience shows that an instrument may undergo small spontaneous variations, apart from those obviously provoked by, e.g., maintenance work. It is accepted that repeated absolute determinations of abundance ratios made with the same mass spectrometer differ as much as mean values provided by different laboratories. But if comparisons are made between samples with slightly different abundances, i.e., if abundances are determined relatively to a standard sample, the accuracy is generally better by a factor of, say, 5 or 10.
>
> The error in the absolute determination quoted above for the C^{12}/C^{13} ratio is estimated to ± 1 per cent. The error in relative abundances is to be evaluated by the statistical treatment of the measurements only, which has been carried out by K. E. Mars.
>
> It is essential that all samples be of the same state of high chemical purity.

CHEMICAL TREATMENT OF THE MATERIAL

The graphite specimens were burned in a stream of pure, dry oxygen, and the resultant carbon dioxide was trapped in saturated barium hydroxide solution. The resulting solution was washed in a dilute solution of barium chloride until the filtrate was neutral to phenolphthalein. The product, barium carbonate, was then dried and finally preserved in glass tubes.

Material which was found to be carbonate-bearing was treated with hydrochloric acid and dried, after which the above process was carried out. Carbonate rocks were treated in the usual manner with dilute hydrochloric acid. In order to ascertain to what degree the chemical treatment could influence the results, specimens 39 and 34, also 27 and 38, were examined by two different methods. Numbers 38 and 39 were dissolved and precipitated in an apparatus in which external air was not permitted to enter until the precipitated carbonate was dry and ready to be transferred to the glass tube.

Specimens 24 and 27 were digested with hydrochloric acid, precipitated, washed, and dried without observing the above precautions. As shown in table 1, the variations are restricted to the limits of experimental error.

SURVEY OF THE INVESTIGATED ROCKS

Of the investigated material, only the specimens taken from the pre-Cambrian formations need be discussed. Owing to the fact that many of the samples were obtained from rather old collections, the descriptions of their geological settings are of a somewhat heterogeneous nature.

Within the "Archean" of Fennoscandia there are three different major units representing three different cycles of orogeny. The oldest are the Svecofennian rocks, which form the greater portion of middle and northern Sweden, as well as southern, northern, and western Finland. The Gothian group of rocks is younger than the above, and they occur in southern and southwestern Sweden. The youngest are the Karelian rocks, and they may represent the same orogeny. Within all these units there occur both supracrustal rocks (vulcanites of various compositions and true sediments) and intrusive rocks, among which granites are the best represented.

DESCRIPTION OF THE MATERIALS INVESTIGATED AND THEIR GEOLOGICAL SETTING

1. *Anthracite from Grythyttan (Sikbergsgruvan).*—The ore at Sikberg is an

TABLE 1

C^{12}/C^{13} RATIOS OF MATERIAL TESTED

SAMPLE	C^{12}/C^{13}	LOCATION	MINERAL	AGE
			Graphite	
1	92.4	Grythyttan	Anthracite in leptite	Svecofen
2	91.7	Norberg	Graphite in leptite	Svecofen
3	90.2	Raitajärvi	Graphite in leptite	Svecofen
4	90.0	Palopöiviö	Graphite in leptite	Svecofen
5	91.5	Kågedal	Graphite in leptite	Svecofen
6	91.0	Malå	Graphite in leptite	Svecofen
7	91.5	Skälsta	Graphite in gneisses	Svecofen
8	88.4	Dannemora	Anthracite in leptite	Svecofen
9	91.9	Dannemora	Mineral pitch in leptite	Svecofen
10	89.3	Tunaberg	Graphite in leptite	Svecofen
11	92.5	Gräsön	Mineral pitch in pegmatite	Svecofen
12	92.3	Nullaberg	Bitumen	Gothian
13	92.4	Billingen	Kolm	Cambrian
14	91.5	Höganäs	Bituminous coal	Liassic
15	91.3	Skåne	Anthracite in limestone	Ordovician
16	91.3	Skåne	Bituminous coal	Cretaceous
17	91.6	Skåne	Graphite from smelting furnace	Recent
18	90.1	Ceylon	Graphite	.....
			Limestone	
19	89.2	Jörn	Limestone in leptite	Svecofen
20	89.0	V. Färnebo	Spilite in leptite	Svecofen
21	89.8	Norsjö	Uralite-porphyrite in leptite	Svecofen
22	89.3	Norsjö	Lime-bearing quartz-porphyry in leptite	Svecofen
23	89.2	Lindsköldsgruvan	Calcite vein in leptite	Svecofen
24	88.9	Alnön	Calcite dykes	Post-Jotnian
25	89.7	Mansjön	Limestone in leptite	Svecofen
26	90.1(?)	Tunaberg	Limestone in leptite	Svecofen
27	88.4	Oaxen	Limestone in leptite	Svecofen
28	88.4	Krokek	Limestone in leptite	Svecofen
29	89.3	Långban	Limestone in leptite	Svecofen
30	89.4	Grythyttan	Spilite in leptite	Svecofen
31	89.5	Dalformationen	Limestone	Karelian
32	89.0	Rättvik	Glauconitic limestone	Ordovician
33	89.3	Borgholm	Tessinilimestone	Cambrian
34	89.2	Skåne	Oölitic limestone	Jurassic
35	89.2	Skåne	Syringophyllum limestone	Silurian
36	88.8	Dalarna	Limestone	Gothlandium
37	89.2	Skåne	Coccolitic limestone	Danien
38	88.4	Oaxen	Limestone in leptite	Svecofen
39	88.1	Skåne	Oölitic limestone	Jurassic
40	89.2	Skåne	Mammillatus limestone	Cretaceous
41	88.1	Skåne	Oölitic limestone	Jurassic

iron ore, also containing limestone and skarn. It is situated in volcanic or sedimentary rocks which exhibit a relatively low grade of metamorphism. Further information concerning the mode of occurrence of the carbon is lacking.

2. *Graphite from the Skrammelfall mine, Norberg.*—The graphite occurs in a synkinematic Svecofennian granite. According to Lindroth (1918), the graphite has clearly an epigenetic occurrence. Minor graphite veins are congregated in a zone a few meters thick, and the graphite migration is accompanied by an intensive alteration of the feldspar of the granite into muscovite.

3, 4. *Graphite from Raitajärvi and Palojärvi.*—The graphite appears as lens-shaped concentrations up to 4–5 meters in thickness and 10–15 meters in length in calcareous quartz-feldspar-biotite gneisses, which are probably of sedimentary origin. These are considered to belong to the Svecofennian cycle (Geijer, 1931).

5, 6. *Graphite from Kågedal and Malå.*—Graphite is an essential constituent of pelitic sediments of the phyllite series of the Skellefte district (Högbom, 1935). The grade of metamorphism in the graphitic rocks investigated should correspond approximately to the epidote-amphibolite facies.

7. *Graphite from Skälsta.*—Concentrations of graphite occur in almandine-bearing gneisses which are probably of sedimentary origin and belong to the Svecofennian rocks of middle Sweden.

8, 9. *Anthracite from Dannemora. Mineral pitch from Dannemora (both from the Ödesgruvan in the Central Field).*—The Dannemora ores are composed of magnetite in a dolomitic limestone and are surrounded by relatively low-metamorphosed Svecofennian rocks (hälleflinta). The graphite-bearing specimens have been obtained from material sent to the Geological Survey of Sweden by one of the mining engineers. Detailed information about the modes of occurrence are lacking.

10. *Graphite from Tunaberg.*—The graphite occurs as small flakes in a coarse limestone which is a member of the Svecofennian supracrustal series. The surrounding rocks consist, for the most part, of veined gneisses with almandite and cordierite.

11. *Mineral pitch from Gräsön.*—The mineral pitch is found in a postkinematic Svecofennian pegmatite on the eastern coast of middle Sweden. The pitch is probably a secondary filling of small cavities in the pegmatite.

12. *Bituminous mass from Nullaberget.*—The carbon occurs in Gothian gneisses as bituminous, pitchlike masses which vary between a few millimeters and 1 cm. in diameter. The gneisses consist mainly of quartz, feldspar, mica, and, less commonly, garnet.

19. *Limestone, Koljärn, Jörn.*—This is a relatively coarse-grained limestone that occurs in the Svecofennian supracrustal series of northern Sweden.

20, 30. *Spilitic greenstone from western Färnebo. Spilite from Grythyttan.*—Both are spilitic greenstones in the Svecofennian supracrustal series.

21, 22. *Calcite-cemented uralite-porphyrite. Lime-bearing quartz-porphyry (both from Norsjö parish in the Skellefte district).*—These represent both calcareous volcanic rocks within the Skellefte field, the calcite brecciating and replacing the vulcanites.

23. *Calcite vein from the Lindsköld mine.*—Thin veins of calcite, containing native arsenic, silver, arsenides of cobalt and nickel, etc., occur as a last stage of mineralization, together with chalcopyrite-pyrrhotite-arsenopyrite ores (Gavelin, 1945).

24. *Calcite dikes, Alnö.*—The calcite in

this area forms dikes which are connected with alkaline rocks of a metasomatic-eruptive origin (von Eckermann, 1948).

25, 26, 27, 28, 29. *Limestone from Mansjön. Limestone from Tunaberg. Limestone from Oaxen. Limestone from Krokek. Limestone from Långban.*—All these rocks are crystalline limestones from limestone beds in the Svecofennian supracrustal formation of middle Sweden, the four first-named being surrounded by gneisses and the last-named occurring in a setting characterized by low-grade metamorphism.

31. *Limestone from the Dal series.*—Limestone beds of this series are composed of relatively well-preserved normal, clastic sediments, probably of Karelidian age.

DISCUSSION OF THE RESULTS OBTAINED

Because the mass-spectrometric measurements in this investigation were made with apparatus not used by the previous workers, two samples of material which has been formerly analyzed, one from Ceylon and one of Swedish Kolm, were tested. These have been examined by Nier and Gulbransen (1939) and by Murphey and Nier (1941), with the results shown in table 2. The different results obtained from the same material by different investigators lie well within the allowable limits of error. Consequently, one may compare the results of this examination directly with the values obtained by Nier and his co-workers.

The results obtained are summarized in table 1 and in figure 1, in which both later and earlier values are presented (Rankama, 1948*b*). The concentration of the C^{12}/C^{13} values in two main groups, which also is apparent in Rankama's survey, is verified by the new results: carbon in carbonates displays, in general, lower values than carbon in noncarbonate rocks.

In figure 2 the analyses of carbon from carbonates are presented separately, the older values being included for the sake of comparison (to the left in fig. 2). The carbonaceous material has been divided into three main groups: (*a*) Phanerozoic carbonaceous sediments; (*b*) pre-Cambrian carbonatites, occurring as interlayered beds in sediments and volcanic rocks of the supracrustal complex; and (*c*) carbonates in calcite dikes, spilites, or rocks in general of a metasomatic origin—thus carbonates the genesis of which cannot have any direct relation to organic material.

TABLE 2

COMPARISON OF THE RESULTS OF VARIOUS INVESTIGATORS

Investigator	Kolm	Graphite, Ceylon
Nier and Murphey	92.4	.....
Nier and Gulbransen	.....	89.8
Murphey	.....	90.2
Mars	92.4	90.1

The distribution of the new analyses agrees fairly well with the earlier results. Among the three different groups in the new material, several diversities are discernible; but the degree to which these may be considered to reflect real variations in the mode of origin and the degree to which they are accidental are impossible to ascertain, at least by a consideration solely of the material at hand. For the continued investigations, one can merely establish the fact that the diagram gives the impression that the oldest limestones have a somewhat greater dispersion of values than do the younger and that the third group seems to represent the minimum dispersion of analyses.

In figure 3 the values have been grouped in a manner analogous to that used in figure 2. If we at first regard only

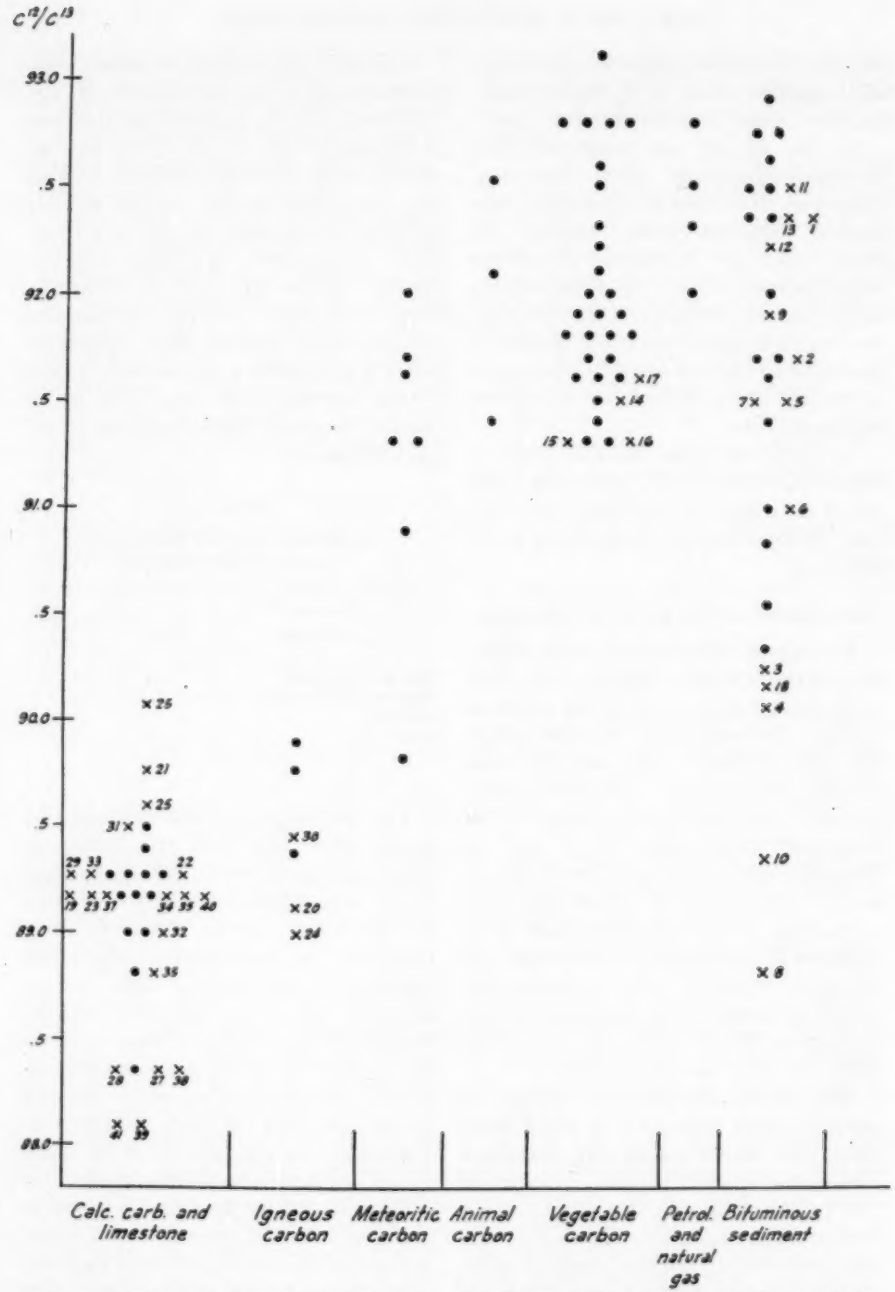

FIG. 1.—C^{12}/C^{13} ratios in carbonaceous materials, classified according to their origin. Dots represent values from Rankama (1948*b*); crosses represent results of the present investigation. Numbers refer to text and table 1.

the new values for carbon from younger (Phanerozoic) formations, we find good agreement between these and the earlier results. A perusal of the diagram leaves one with the impression that the value 91.3 represents a bottom limit for organically formed carbon. It is, however, noteworthy that in the earlier surveys as well as in the present investigation the carbon from pre-Cambrian sedimentary formations (usually graphite) also shows considerably lower values. It ought to be relatively simple to seek the reason for these circumstances in the more variable intricate origin of the Archean rocks. As yet, however, it is impossible to name the factors which have given rise to the above-mentioned variations in the carbon of the older rocks. The role played by temperature is shown by the value obtained on graphite from a smelting furnace, the carbon of which has been subjected to high temperature. Its value, 91.6, falls inside the field of distribution

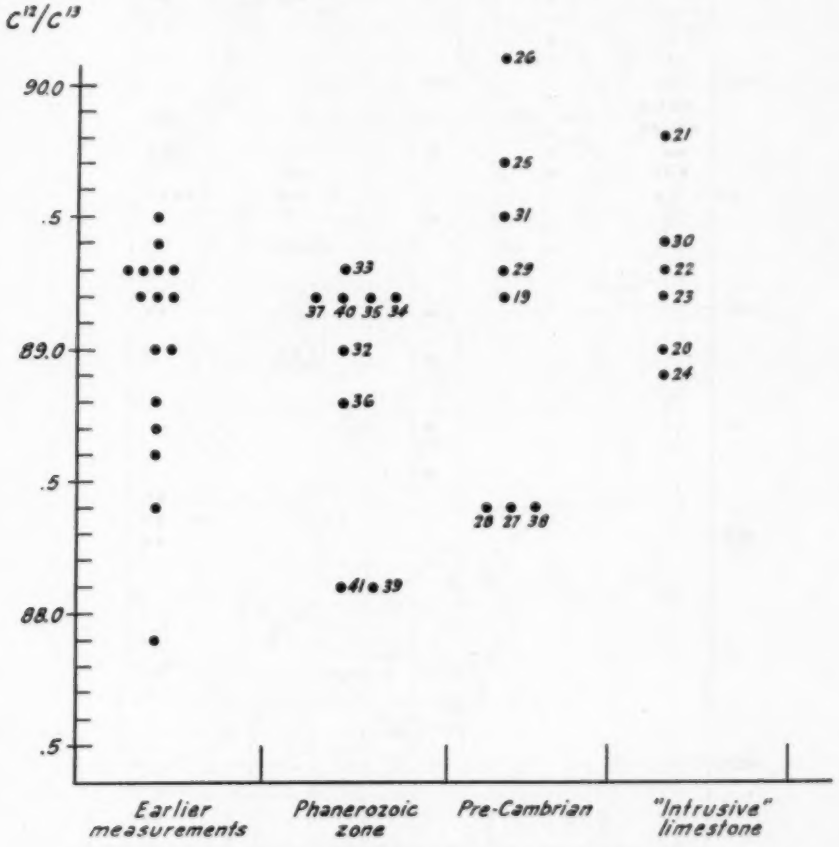

FIG. 2.—Distribution of the abundance ratios C^{12}/C^{13} of limestones

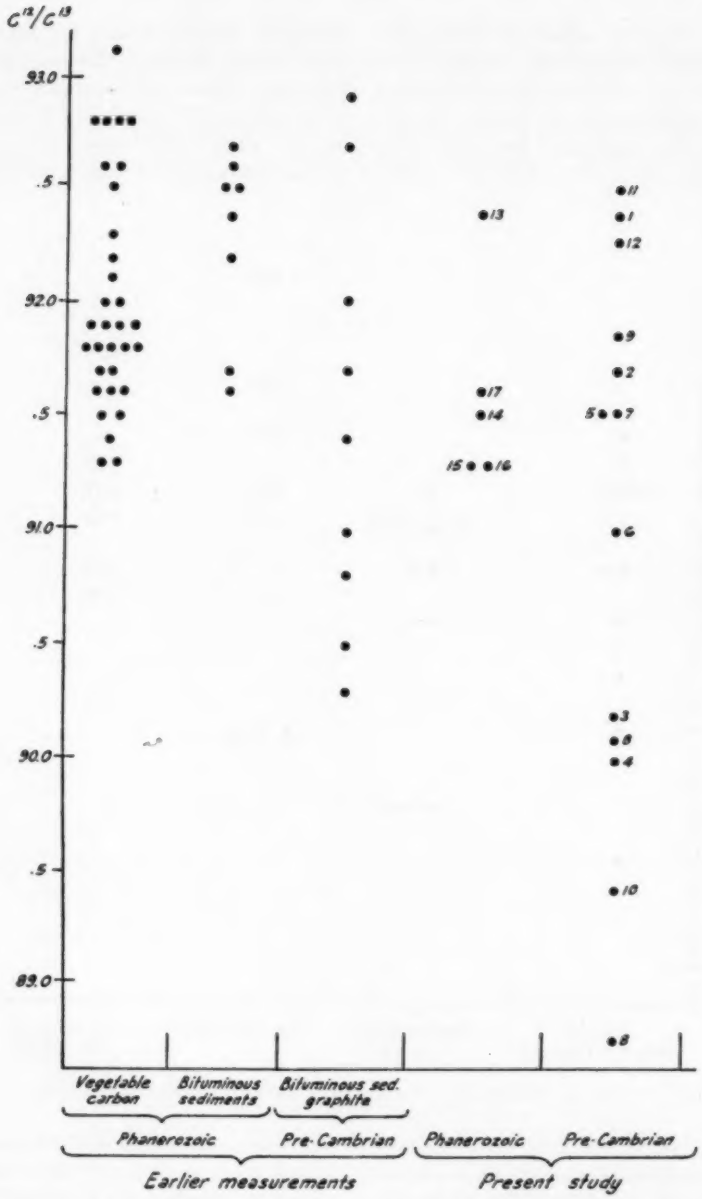

FIG. 3.—Distribution of the abundance ratios C^{12}/C^{13} of graphite

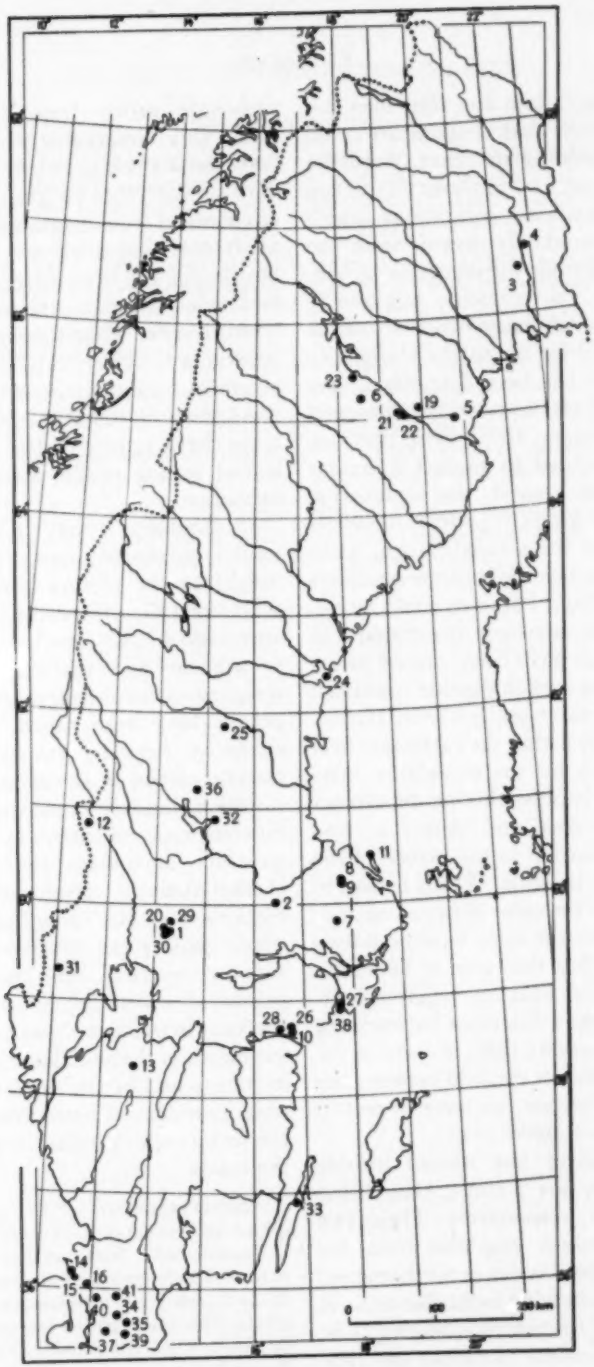

FIG. 4.—Location of samples in Sweden

for vegetable carbon and thus does not indicate in itself that temperature could have any deciding influence. Actually, there are now five analyses of carbon from pre-Cambrian formations which clearly and markedly diverge from the field of distribution for vegetable carbon. Analysis no. 10 represents graphite in the form of small flakes which appear in limestone and for which the abundance ratio C^{12}/C^{13} has been determined (no. 26). The values 89.4 for graphite and 90.1 for limestone are so close that one would be inclined to suspect a similar origin. In this respect, the explanation made by Rankama (1948*b*) to clear up the nature of the anomalous (or, more nearly, the carbonatic) isotope quotients for graphite from Parainen could be applied here. He considers the graphite in this locality to have been formed by reduction of the carbon dioxide contained in the limestone. Sample 8 from Dannemora also falls within the carbonate field of distribution for the abundance ratio C^{12}/C^{13}, and, because this ore deposit occurs in limestone and skarn, a close genetic relationship to the carbon of the carbonates is possible. Worth noting in that respect is the value obtained on mineral pitch from the same locality, namely, 91.9, which is thus seen to lie within the distribution field for vegetable carbon. The marked difference between the two values suggests that, in spite of the close association in the field between the two types of carbon, we have to reckon with carbons of unlike origin.

The remaining low values include those given by nos. 3 and 4, these being 90.2 and 90.1, respectively. These two analyses represent graphites from the same supracrustal series in northernmost Sweden. Lime-bearing rocks also occur in the vicinity of the graphite-bearing beds, but it is not possible to deduce any relationship between the graphites and this carbonate-carbon from the available data. Very remarkable, however, is the fact that Rankama (1948*a*) has found a very similar value for graphite of northern Finland from a formation which, to all intents and purposes, is the same, both in age and in position, as the above-mentioned supracrustal rocks on the Swedish side. This graphite (no. 6 in Rankama's work) exhibits the same anomalous value, 90.0. We may ask if this agreement reflects any special conditions characteristic of the age and geological setting of the above-mentioned formation.

In summary, it may be said that the results presented above lend further weight to the picture obtained earlier concerning the differences in the abundance ratio C^{12}/C^{13} due to carbon bound as carbonate and other carbon. Many interesting questions pertaining to petrogenesis have been raised, such as the similarity between graphite and carbonatic carbon in the same mineral association, the lack of similarity between different types of carbon in the same association, anomalous abundance ratios characteristic of certain geological formations, etc., the value and content of which aspects can first be judged in a wider connection. The purpose of the continued investigations is to increase the knowledge of the laws governing the variations in the abundance ratio C^{12}/C^{13} in nature and at the same time, if possible, to widen our perception concerning the factors which influence the values of the ratios.

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ON THE VARIATIONS IN THE RELATIVE ABUNDANCE OF THE CARBON ISOTOPES IN CARBONATE MINERALS[1]

FRANS E. WICKMAN,[2] R. BLIX,[2] AND H. VON UBISCH[3]

ABSTRACT

The ratio C^{12}/C^{13} for forty-five samples of eleven carbonate minerals has been measured. The ratios of dolomites are all under 89, the ratios of carbonates from the oxidation zone of ores are all over 89, and the ratios of other carbonate minerals are distributed over a greater range. The distribution of the carbon isotope ratios is discussed with special reference to the genetic relationships, and the results are shown to be in agreement with theoretical considerations.

INTRODUCTION

Nier and Gulbransen (1939) have shown that the abundance ratios of the two carbon isotopes C^{12} and C^{13} vary in natural materials. A summary of all recent investigations may be found in a paper by Rankama (1948). From his table 7 (pp. 204–205) it can be seen that all limestones and calcium carbonates so far investigated have a ratio in the range 87.9–89.9, the median value being in the vicinity of 89.3.

So far no other carbonate minerals have been investigated, and this gap in our knowledge makes most geological problems very difficult to discuss in terms of isotope ratios. The present study is to be regarded as only a preliminary survey of the field, but we hope it will show some of the interesting problems connected with isotope investigations.

THE SAMPLES AND THEIR TREATMENT

All samples used in this investigation are from specimens in the collections of the Riksmuseum in Stockholm, the numbering corresponding to that of the museum. They were all (including witherite!) converted into barium carbonate. Great care was exercised in order to prevent contamination by atmospheric carbon dioxide and to secure complete decomposition of the original carbonate as well as complete precipitation of the barium carbonate.

For the preparation we used a decomposition flask, some absorption flasks, and two gas-washing cylinders. The decomposition flask was a 100-ml., three-neck, round-bottom flask with rubber stoppers fitted into its necks. To one was attached a short Liebig condenser, to another a pear-shaped separatory funnel, and to the third a glass tube—the air inlet tube—which reached almost to the bottom of the decomposition flask. Outside the flask the air inlet tube was equipped with a glass stopcock. An absorption flask consisted of a 500-ml. flask with a rubber stopper which carried a gas inlet tube and an evacuation tube. The gas inlet tube was a glass tube with a glass stopcock and reached almost to the bottom of the absorption flask. The evacuation tube was also supplied with a glass stopcock but reached only to just beneath the rubber stopper. The two gas-washing cylinders were of the Friedrichs type and contained 50 per cent KOH solution. The gas-washing cylinders coupled in series were connected

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with the gas inlet tube of the decomposition flask, and the latter was connected with the gas inlet tube of the absorption flask by the condenser and a glass tube. The vacuum line was connected with the evacuation tube of the absorption flask.

Coarse pieces of the sample, equivalent to about 2 g. $BaCO_3$, and 10 ml. H_2O were placed in the decomposition flask, after which the whole apparatus was evacuated to about 20 mm. Hg. By opening the gas inlet stopcock, the apparatus was filled with air which had been freed from carbon dioxide by bubbling through the gas-washing cylinders. The absorption flask was filled with 200 ml. of a 0.15 N $Ba(OH)_2$ solution which contained about 1 per cent $BaCl_2$; and the apparatus was once again evacuated.

Now 40 ml. of 8–12 per cent hydrochloric acid (or, in some cases, perchloric acid) were added slowly from the separatory funnel. The solution containing the sample was boiled until the decomposition was complete, after which a slow stream of air was bubbled through the solution, which was kept boiling. The addition of acid, the heat from the burner, and the air inlet were regulated in such a way that a slow constant flow of gas was obtained through the absorption flask. From time to time the absorption flask was shaken vigorously.

At the conclusion of these operations, the excess of $Ba(OH)_2$ was neutralized with 0.2 N HCl, using phenolphthalein as indicator. The whole content of the absorption flask was then transferred to a closed 500-ml. Erlenmeyer flask and heated for 16 hours in a thermostat at 100° C. in order to convert the fine-grained barium carbonate precipitate into a more coarse-grained form. The precipitate was filtered through a sintered glass crucible, washed with cold water until it was free of $BaCl_2$, and dried at 110° C.

The mass spectrometric measurements were performed by Dr. H. von Ubisch at the Department of Chemistry, Karolinska Institutet, Stockholm. As an internal standard a large quantity (5 kg.) of commercial $BaCO_3$ was used. The value of the C^{12}/C^{13} ratio of this standard was chosen as 89.5, and it is the hope of the present writers that this standard will make it possible to reduce the values to a common basis and thus permit intercalibration between different investigators. Samples of this material will be gladly furnished to all inquirers. The value has been chosen so that our values can be compared with those of the Nier school and those of K. E. Mars (1951). The usual O^{17} correction was applied to our values.

DISCUSSION

The C^{12}/C^{13} ratios of our forty-five samples are to be regarded as accurate to within 0.3 unit. In most cases they are accurate to within 0.1 unit. In order to compare our values with those of earlier investigators, figure 1 was prepared. The values of calcites and limestones from previous investigations (after Rankama) have also been plotted on this figure, and it is evident that they cover the same range of values as those of the other carbonate minerals. This is not surprising if we remember that most other carbonates are directly or indirectly derived from limestones or calcites.

At first sight, a comparison of the distribution ranges of the various carbonate minerals does not yield much of geological interest. Some carbonates, such as azurite and cerussite, have their values concentrated around the greater values, whereas others, like dolomite, are concentrated around the lesser

values, and still others are distributed over the whole range. It must be remembered, however, that the number of specimens of each separate mineral is small, which means that we must be very careful in drawing conclusions. As

group. In most cases the mechanism of their formation is generally assumed to be the following. Because of the presence of oxygen in the air and in ground water, sulfides are no longer stable, and so sulfuric acid is formed, to give acid solu-

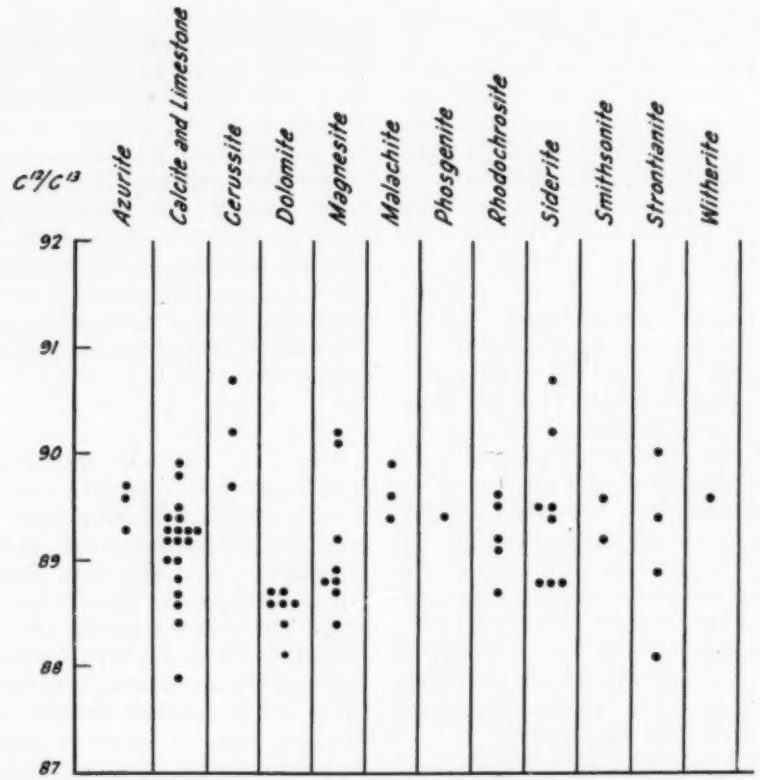

FIG. 1.—The C^{12}/C^{13} ratio of the forty-five measured samples compared with the values of calcites and limestones of earlier investigators (after Rankama, 1948).

it is well known that carbonates may be formed in various ways, it might be most profitable for our discussion to group the material according to paragenetic principles.

Those carbonate minerals which are developed in connection with oxidation of sulfide ores form one characteristic

tions containing copper, lead, and zinc. These solutions react with adjacent limestones or other carbonates, forming minerals like azurite, malachite, cerussite, phosgenite, and smithsonite. In some cases malachite might be formed by a more direct reaction between native copper and carbon dioxide from the air and

water. This would mean that generally the ratio C^{12}/C^{13} of the carbonates of the oxidation zone would be related to the ratio of the adjacent limestone or dolomite. We have tabulated the carbonates from the oxidation zone and their relations to carbonates in the immediate surroundings (table 1) in order to facilitate a comparison. A look at this table will show that there is no such simple relation between the C^{12}/C^{13} ratio and the presence of limestones or similar rocks. On the other hand, it is evident the values of the oxidation-zone carbonates are higher than those of dolomites and even higher than the values of most limestones. The reason for this is certainly that we have to deal with very complex phenomena, in which different factors co-operate. One of these factors might be that these minerals have been formed quite recently near the surface, which means that carbon dioxide from the oxidation of deceased organisms might, in many cases, be important. The other carbonates, which can be formed in various ways, will be discussed one by one.

Dolomites represent the most homogeneous group of the minerals so far studied, with values exclusively under 89. The paragenetic relationships are given in table 2. It is quite clear that the selection of specimens in this case is not quite suitable because there is only one specimen from an ore vein. We hope in a later paper to give a more complete paragenetic list. On the other hand, we have dolomites of various ages. Those from Långban and Bergsäng date back at least 1,200 million years, the one from Ljusnedal 500–600 million years, and the specimen from Italy only about 150–200 million years. It is obvious that there is no simple age effect here. The further discussion of this table will be postponed

TABLE 1

MINERALS FROM THE OXIDATION ZONE OF ORES

Mineral	Locality	Riksmuseum Collection No.	C^{12}/C^{13}	Remarks on Geology
Cerussite	Leadhills, Scotland	LK 4183	90.7	No limestones; calcite and dolomite gangue minerals
Cerussite	Broken Hill, New South Wales, Australia	334524	90.2	No limestones
Malachite	Nischni Tagilsk, Ural, U.S.S.R.	38377	89.9	Occurs in pockets in limestones
Cerussite	Nertschinsk, Transbaikalia	LK 4162	89.7	?
Azurite	Chessy, France	38379	89.7	No limestones
Azurite	Burra-Burra mine, South Australia	G 10690	89.6	Occurs in sedimentary limestones
Malachite	Burra-Burra mine, South Australia	G 10611	89.6	Occurs in sedimentary limestones
Smithsonite	Broken Hill, Northern Rhodesia	31005	89.6	Occurs with dolomites
Malachite	Punta de Cobre, Atacama, Chile	G 10574	89.4	No connection with limestones; calcite occurs in the veins
Phosgenite	Matlock, Derbyshire, England	23676	89.4	Occurs in limestones together with calcite, etc.
Azurite	Solotuschinsk, Kolyvan, Altai, U.S.S.R.	LK 4102	89.3	?
Smithsonite	Liége, Belgium	G 10242	89.2	Limestones present

until we can make comparisons with magnesite.

Magnesites show a wide distribution of their C^{12}/C^{13} values, but if we tabulate them, together with paragenetic notes, certain relationships are quite obvious (table 3). A glance at this table shows that those magnesites which have been formed by carbon dioxide metasomatism from serpentine or other magnesium minerals have a higher C^{12}/C^{13} ratio than those which have been formed by magnesium metasomatism. This seems to be true even in other cases. If we compare our values for dolomite with those for magnesite, it is evident that we have the same phenomena. Rankama (1948) has already shown that "igneous carbon" is characterized by higher values of the ratio than are sediments. The same tendency is easily detectable in Mars's material (1951).

TABLE 2

C^{12}/C^{13} VALUES OF DOLOMITES

Mineral	Locality	Riksmuseum Collection No.	C^{12}/C^{13}	Mode of Formation
Dolomite.....	Långban, Värmland, Sweden	38916	88.7	Metasomatized sediment
Dolomite.....	Freiberg, Saxony	G 9992	88.7	Ore vein
Dolomite.....	Hasselhöjden, Grythytte Co., Västmanland, Sweden	G 9982	88.6	Metasomatized sediment
Dolomite.....	Westchester Co., New York, U.S.A.	LK 4463	88.6	Metasomatized sediment
Dolomite.....	Vesuv, Italy	LK 4453	88.6	Metasomatized sediment
Dolomite.....	Bergsäng, Nora Co., Västmanland, Sweden	LK 4432	88.4	Metasomatized sediment
Dolomite.....	Ljusnedal, Härjedalen, Sweden	LK 4422	88.1	Metasomatized sediment

TABLE 3

C^{12}/C^{13} VALUES OF MAGNESITES

Mineral	Locality	Riksmuseum Collection No.	C^{12}/C^{13}	Mode of Formation
Magnesite.....	Mussinet, Piemonte, Italy	G 10061	90.2	From serpentine
Magnesite.....	Cecil Co., Maryland, U.S.A.	G 10066	90.1	From serpentine
Magnesite.....	Snarum, Norway	24153	89.2	From serpentine
Magnesite.....	Zillerthal, Tirol	G 10423	88.9	From serpentine
Magnesite.....	Åpartjokko, Jokkmokk Co., Lappland, Sweden	410058	88.8	Metasomatism of limestone or dolomite
Magnesite.....	St. Kathrein, Bruck, Styria, Austria	LK 3948	88.8	Metasomatism of limestone or dolomite
Magnesite.....	Ratkoszuha, Gömör, Hungary	335108	88.7	Metasomatism of limestone or dolomite
Magnesite.....	Harz, Germany	G 10052	88.4	Metasomatism of limestone or dolomite

We might here introduce a remark on the low values of some of the Grenville limestones investigated by Murphey (see Rankama, 1948). The Grenville limestone is dolomitic to a certain extent, and it would be interesting to know whether the exceptionally low values correspond to dolomitization.

There are also some paragenetic types of magnesites which are not present in our list, but we hope to treat them in a forthcoming paper. Rhodochrosite is not so well represented in our material (table 4). These values are in agreement with those already obtained. The sediment gives the lowest value, and the ore vein and Steinheim at Hanau gives a high value of the ratio C^{12}/C^{13}. For the moment it is impossible to decide whether the carbon dioxide in the mineral comes from the basalt itself or whether it has something to do with the soil which was buried by the basalt at the time of eruption. The latter possibility is the more probable,

TABLE 4

C^{12}/C^{13} VALUES OF RHODOCHROSITES

Mineral	Locality	Riksmuseum Collection No.	C^{12}/C^{13}	Mode of Formation
Rhodochrosite.....	Bescheert Glück, Freiberg, Saxony	G 10216	89.6	Ore vein
Rhodochrosite.....	Dietz, Nassau, Germany	333668	89.5	Secondary in gossan
Rhodochrosite.....	Marhult mine, Västergötland, Sweden	G 10190	89.2	Secondary (?)*
Rhodochrosite.....	Saguache Co., Colorado, U.S.A.	251766	89.1	Ore vein
Rhodochrosite.....	Långban, Värmland, Sweden	G 10199	88.7	Sedimentary

* P. Geijer, personal communication.

TABLE 5

C^{12}/C^{13} VALUES OF SIDERITES

Mineral	Locality	Riksmuseum Collection No.	C^{12}/C^{13}	Mode of Formation
Sphaerosiderite..	Steinheim, Hanau, Hessen, Germany	G 10141	90.7	Cavities in basalt
Siderite.....	Gr. Reussisches Haus, Lobenstein, Thüringen, Germany	G 10158	90.2	Ore vein
Siderite.....	Bleka mine, Telemark, Norway	335319	89.5	Ore vein
Siderite.....	Lammrichskaule, Horhausen, Germany	G 10127	89.5	Ore vein
Siderite.....	Ivigtut, Greenland	83:537	89.4	Pegmatite
Siderite.....	Glasnäs, Ältrå Co., Värmland, Sweden	G 10087	88.8	Ore vein (?)
Siderite.....	Rozsnyo, Hungary	335109	88.8	Ore vein (?)
Siderite.....	Finnhult mine, Grythyttan Co., Västmanland, Sweden	G 10105	88.8	Sediment

oxidation occurrences show higher values of the ratio.

Siderite is one of the most common carbonates and it is therefore of considerable interest to study the distribution of its C^{12}/C^{13} values (table 5). It is regrettable that we cannot present in this paper data from a more complete paragenetic material, but we hope to do so in a later publication. We observe that the well-known sphaerosiderite from especially since the cavities occur in connection with vertical fissures, but the problem then arises as to whether we are observing a "normal" soil carbon dioxide or a contamination by carbon dioxide generated by oxidation of the lignite found beneath the basalt. The other siderites show a great range of variation, but it is for the moment best to postpone the discussion until more material has been investigated.

We have only four samples of strontianite (table 6). The high value of the American strontianite is remarkable. For the moment, it is impossible to guess the reason for this, but possibly the oxidation of organic matter has produced CO_2, which has become mixed with ordinary sedimentary CO_2. Only thorough investigations can clarify this point. The other strontianites confirm our general picture.

The value 89.6 for the only sample of witherite (Fallowfield, Northumberland, England; Riksmuseum collection no. G 10417) is quite normal for a sample formed by CO_2 metasomatism from barite. We might also be interested in the question of whether any specific area or district gives a constant C^{12}/C^{13} ratio. Our material has not been selected with this in mind, but in a few cases we have more than one mineral from the same place (table 7). From this table we see that Långban and Burra-Burra show the same ratios, but the ore-vein minerals from Freiberg show a considerable difference. This is to be expected if we remember that the first two are paragenetically much more homogeneous than the third. In ore veins the composition and temperature of the solutions which have formed the minerals have varied very strongly, and the formation of the minerals in the same vein or in different veins occurs over long intervals of time.

TABLE 6

C^{12}/C^{13} VALUES OF STRONTIANITES

Mineral	Locality	Riksmuseum Collection No.	C^{12}/C^{13}	Mode of Formation
Strontianite....	Schoharie, New York, U.S.A.	LK 4259	90.0	Sediment
Strontianite....	Strontian, Scotland	LK 7785	89.4	Ore vein
Strontianite....	Drensteinfurt, Westphalia, Germany	G 10439	88.9	Sediment
Strontianite....	Sendenhorst, Westphalia, Germany	LK 4267	88.1	Sediment

TABLE 7

C^{12}/C^{13} VALUES OF MINERALS FROM THE SAME LOCALITIES

Mineral	Locality	Riksmuseum Collection No.	C^{12}/C^{13}	Mode of Formation
Azurite.....	Burra-Burra mine, South Australia	G 10690	89.6	Oxidation zone
Malachite.....	Burra-Burra mine, South Australia	G 10611	89.6	Oxidation zone
Dolomite.....	Freiberg, Saxony	G 9992	88.7	Ore vein
Rhodochrosite.....	Bescheert Blück, Freiberg, Saxony	G 10216	89.6	Ore vein
Dolomite.....	Långban, Värmland, Sweden	38916	88.7	Metamorphosed sediment
Rhodochrosite.....	Långban, Värmland, Sweden	G 10199	88.7	Metamorphosed sediment

GENERAL DISCUSSION AND CONCLUSIONS

In the preceding paragraphs we have discussed the various carbonate minerals from a paragenetic viewpoint, and from this discussion we have obtained some rules which can be expressed as follows:

1. In general, carbonate minerals show

the same range of variation as does calcium carbonate.

2. Those carbonate minerals which are formed in the oxidation zone show, in general, some enrichment of the light carbon isotope in comparison with sedimentary limestones and dolomites.

3. Those minerals which are formed by "cation metasomatism" show an enrichment of the heavy carbon isotope. This is especially evident in the case of dolomite and magnesite.

These conclusions are, of course, not very well founded, and we hope in the near future to publish more data. Nevertheless, we are confident of our results and consider them valid. It might be of interest to discuss what may be expected from what we know about the formation of carbonate minerals and the enrichment of isotopes and see whether the results of such a discussion are in agreement with our results. Carbonate minerals might form in three different ways. They might be precipitated from solution, be formed by a reaction between a solid and gaseous carbonate dioxide, or result from cation exchange between a carbonate crystal and its environment.

The first possibility is the most common one. In general, nothing can be stated about the ratio C^{12}/C^{13} in this case. It is dependent on the composition, the temperature, and the pressure of the solution from which the carbonate is precipitated. The most important source of limestones is the sea. In this case we can expect that the C^{12}/C^{13} ratio will vary about a mean value, which is probably around 89.3 (Murphey, 1941).

The second possibility is very rarely realized. Some malachites are believed to be formed in this way, but it is uncertain whether or not liquid water has always been present. Neither, in this case, is it possible to state anything about the values to be expected. They are dependent on the same factors that are important in the first case. Quite generally it can be stated that the sea is the main carbon dioxide regulator of the atmosphere. However, local variations might be very large, depending on the oxidation of dead organisms.

The third case is a very interesting one. It is a form of metasomatism and in its proper sense means that we have a one-one substitution of cations in a crystal structure. A well-known example of this is the formation of certain dolomites from calcite. We can also say that this type of metasomatism can occur only within an isomorphous series, e.g., calcite—(dolomite)—magnesite—siderite—rhodochrosite—smithsonite or aragonite—strontianite—witherite—cerussite.

The mechanism of the reaction is most easily illustrated by an example. If we have a calcite bed full of fissures, through which a solution of $MgCl_2$ percolates very slowly, there will be an exchange of cations between the solution and the crystal. The solution will also be saturated with CO_3^- ions, and, consequently, there will be an isotope exchange reaction between the ions in the solution and those in the crystals. As is well known, the solution will enrich the light carbon isotope, and it will preferentially be transported away with the solution. If this be correct, we must expect an enrichment of the heavy isotope in the dolomite or magnesite formed, and the enrichment will be a function of the time, the temperature and pressure, the composition of the solutions, and the original limestone. In most cases the original carbonate will consist of marine limestones showing values around 89.3. We can conclude that we should expect values under 89.3 for minerals formed in this way. This is in complete agreement

with the values found for dolomites and magnesites formed in this fashion. In two of the strontianite cases this theory is consistent with our measurements; in the third—the American—it is not. There could be many explanations for this exception, but so far the real one remains unknown. It is to be hoped that further investigations will clear up this point and give us a clearer understanding of the variation of the distribution of the C^{12}/C^{13} values of the ore-vein minerals and the oxidation-zone minerals.

ACKNOWLEDGMENTS.—This investigation has been supported by grants from the Swedish Natural Science Research Council, which is gratefully acknowledged. We wish to thank Professor E. Hammarsten, Department of Chemistry, Karolinska Institutet, Stockholm, for his courtesy in permitting us to have our samples analyzed at his institution.

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DIFFERENTIATION IN MAGMAS OF THE KEWEENAWAN SERIES[1]

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ABSTRACT

The Greenstone flow, a thick, basaltic flow of the Keweenawan series of Michigan, offers a unique opportunity for the study of differentiation in basaltic magma. Differentiation trends in the magma of the Greenstone flow during crystallization have been computed according to two hypotheses as to the manner in which the flow solidified. It was found that the ratio of iron oxides to magnesia increased in the magma during crystallization and that there was a slight to moderate absolute enrichment of the magma in Fe, Ti, Mn, Cu, P, Si, Na, and K until the flow was nearly solid. A residual magma was produced that was rich in silica and alkalies and deficient in the remaining constituents. Magma trends in the lavas of the Keweenawan series and in genetically related intrusives have also been studied and compared with those found in the Greenstone flow.

INTRODUCTION

The problem of composition trends in basaltic magma during crystallization has long been a subject of controversy. Bowen (1928, pp. 80–83) has favored alkali and silica enrichment of the residual liquid; Fenner (1931, 1938) has contended that iron enrichment is also important; and other petrologists have supported one or the other of these theories. Walker and Poldervaart (1949, pp. 656–662) have ably summarized the most important contributions by petrologists to this problem.

In general, petrologists have restricted their attention to the differentiation products formed during the crystallization of basaltic magma and have not computed quantitatively the successive changes in composition of the magma itself during crystallization. To the writer's knowledge, the only attempt to determine accurately the liquid line of descent of basaltic magma during crystallization was made by Wager and Deer (1939) in an excellent paper on the Skaergaard intrusion of East Greenland. These authors were handicapped because half of the intrusive is not exposed and the composition of the magma was modified to an unknown extent, particularly during the late stages of crystallization, by the assimilation of sialic material from the older rocks into which the magma was intruded.

The Greenstone flow of the Michigan copper district offers a unique opportunity for detailed study of the successive changes in composition of a basaltic magma during crystallization, and the writer therefore presents in this paper the results of such a study in the hope that they will be of interest to other petrologists.

A complete section through the flow is represented by cores from three overlapping diamond-drill holes, and Broderick (1935) and the writer (Cornwall, 1951*a*) have sampled the flow from top to bottom, taking uniformly sized chips of each unit from the drill core at close, regularly spaced intervals. The samples obtained from the drill core should quantitatively represent accurately the differentiation products of the flow because the exact thickness of the units in the flow are known and the units, except the small granophyre dikes, are tabular in a plane parallel to the flow and perpendicu-

[1] Published by permission of the director, U.S. Geological Survey. Manuscript received August 24, 1950.

TABLE 1

CHEMICAL ANALYSES OF THE GREENSTONE FLOW*

	Sample Number and Rock Type								
	3132 Basalt	3134 Basalt	G140 Pegmatitic Layer	G26 Granophyre	3138 Basalt	3140 Pegmatitic Layer	G253 Pegmatitic Layer	3142 Basalt	G207 Pegmatitic Layer
Width (feet)	176	86	23	2	56	4	7	65	7
SiO_2	47.85	47.76	50.19	63.64	48.67	49.25	47.30	48.55	48.03
Al_2O_3	16.88	16.50	13.91	12.92	17.16	10.96	14.72	16.88	13.68
Fe_2O_3	4.18	4.59	3.76	3.18	3.95	4.98	3.34	3.62	3.83
FeO	6.75	6.74	10.44	2.80	7.81	10.78	9.23	7.99	7.62
MgO	6.94	7.08	3.78	1.77	4.73	3.74	4.55	4.96	5.44
CaO	10.69	10.56	6.57	6.01	9.42	9.44	10.61	9.71	13.35
Na_2O	2.40	2.48	3.40	3.37	3.22	3.66	3.65	3.34	2.26
K_2O	0.33	0.37	1.82	3.63	0.69	0.75	0.22	0.56	0.91
H_2O plus	1.97	1.89	2.63	1.50	1.88	1.37	2.94	2.04	2.37
CO_2	0.13	0.07	0.02	0.01	0.05	0.06	0.24	0.06	0.04
TiO_2	1.42	1.57	2.74	0.85	1.95	4.32	2.61	1.95	2.00
P_2O_5	0.18	0.19	0.43	0.17	0.24	0.40	0.28	0.20	0.23
S	0.083	0.015	0.05	0.02	0.016	0.022	0.03	0.012	0.02
Cu	0.015	0.007	0.030	0.007	0.011	0.029	0.035	0.009	0.010
MnO	0.16	0.17	0.22	0.11	0.17	0.25	0.19	0.17	0.19
Total	99.98	100.00	99.99	99.99	99.97	100.01	99.95	100.05	99.98
Total Fe as FeO	10.52	10.88	13.81	5.65	11.37	15.26	12.24	11.25	11.07
Sp. gr.	2.862	2.900	2.98	2.71	2.875	3.084	2.92	2.915	3.02

	Sample Number and Rock Type								
	3144 Basalt	G453 Pegmatitic Layer	3146 Basalt	G559 Pegmatitic Layer	3148 Basalt	3150 Basalt	3152 Basalt	3154 Basalt	Weighted (Liquid 1) Average
Width (feet)	150	5	137	7	144	144	144	142	1,299
SiO_2	48.32	45.12	48.84	47.56	47.46	47.39	46.37	47.57	47.84
Al_2O_3	17.32	13.32	16.90	13.60	18.26	18.54	16.50	16.10	16.98
Fe_2O_3	3.86	3.90	2.49	2.43	2.96	2.46	1.90	2.64	3.18
FeO	7.52	9.78	8.65	8.95	8.00	7.62	8.79	8.45	7.92
MgO	4.84	6.69	5.58	6.49	6.25	6.85	10.16	8.62	6.73
CaO	10.03	9.92	8.88	12.71	10.41	10.76	9.85	9.58	10.01
Na_2O	3.03	2.26	3.45	2.50	2.42	2.30	1.94	2.34	2.63
K_2O	0.72	1.47	0.62	0.57	0.32	0.28	0.24	0.54	0.48
H_2O plus	1.89	3.95	2.51	2.56	2.23	2.25	2.77	2.33	2.23
CO_2	0.08	0.04	0.06	0.00	0.06	0.08	0.08	0.09	0.08
TiO_2	1.93	2.78	1.64	2.15	1.27	1.17	1.09	1.42	1.53
P_2O_5	0.25	0.48	0.17	0.17	0.15	0.15	0.11	0.15	0.18
S	0.018	0.03	0.021	0.02	0.022	0.014	0.014	0.011	0.026
Cu	0.017	0.037	0.011	0.038	0.013	0.011	0.011	0.008	0.012
MnO	0.18	0.21	0.17	0.22	0.16	0.15	0.16	0.17	0.168
Total	100.01	99.99	99.99	99.97	99.98	100.02	99.98	100.02	100.00
Total Fe as FeO	11.00	13.28	10.90	11.14	10.67	9.83	10.54	10.82	10.78
Sp. gr.	2.864	2.98	2.903	2.98	2.861	2.873	2.903	2.893	

* Analyses G26, G140, G253, G207, G453, and G559 were obtained by the writer (1951a), the remaining analyses by Broderick (1935); all analyses recalculated to 100 per cent after deduction of H_2O minus; other minor adjustments also made to permit quantitative combination of Broderick's and the writer's analyses; arranged in stratigraphic order from top at left to bottom at right; analysts, R. B. Ellestad, S. Goldich, and L. C. Peck, Rock Analysis Laboratory, University of Minnesota.

lar to the drill holes. Furthermore, the lava probably was not modified in any way by assimilation of older rocks during crystallization.

Although the quantitative information on the Greenstone flow is unusually complete, the computed magma compositions may be slightly inaccurate because certain necessarily arbitrary assumptions as to the sequence of formation of solid fractions may not be absolutely correct. The extent to which the more volatile constituents escaped during solidification is also unknown. Nevertheless, the general trends of the major constituents in the magma during solidification must be nearly right.

THE GREENSTONE FLOW

GENERAL DESCRIPTION

The Greenstone flow is the thickest flow in the Keweenawan series of the Michigan copper district and ranges in thickness from 1,100 to 1,400 feet for a strike length of 30 miles west from Keweenaw Point. The flow is an ophitic olivine basalt that contains pegmatitic layers and lenses in its upper half. The pegmatitic layers are coarse-grained facies of the ophitic basalt and are oriented parallel to the plane of the flow. Small amounts of interstitial granophyre and small granophyre dikes, generally cross-cutting, are associated with the pegmatitic layers, particularly in the upper part of the pegmatitic zone. Two concentrations of olivine occur in the flow, one near the base, and another near the middle, just above the lowest pegmatitic layers. The basalt consists of labradorite, augite, and olivine, with minor amounts of ilmenite, magnetite, pigeonite, hypersthene, and chlorite, and the pegmatitic layers are composed of albite, augite, and moderate amounts of magnetite, ilmenite, chlorite, epidote, and prehnite.

The Greenstone flow has been systematically sampled and described in detail by Broderick (1935) and the writer (1951*a*), and further descriptive details are therefore omitted from the present discussion. Chemical analyses are shown in table 1. Figure 1 is a detailed cross section of the flow at Delaware, Keweenaw County, Michigan, where it was sampled. The units sampled and the numbers of the samples are also shown. The granophyre shown in figure 1 was not actually found in the diamond-drill core but was projected into the section on the basis of field data. The granophyre sample, G26, was obtained from a cross-cutting dike in the Greenstone flow, 5 miles east of Delaware.

To determine the composition of the magma of the Greenstone flow at successive stages during crystallization, the writer computed the amount in pounds of each constituent in each sample for a column of rock across the flow with a cross section of 1 square foot. The granophyre, represented by analysis G26, was assumed to be the last liquid to crystallize in the flow. Successive solid fractions were added to this and earlier liquids obtained until finally the original magma was determined.

Two hypotheses have been presented by the writer (1951*a*) as to the manner in which the flow solidified. Under both hypotheses it was assumed that during the early and middle stages of solidification the flow cooled and crystallized inward from both the top and the bottom. Cooling was predominantly from the top, as shown by the much greater thickness of the upper chill zone, but crystals were settling to the bottom while magma was freezing to the top.

The sequence of formation of the rocks

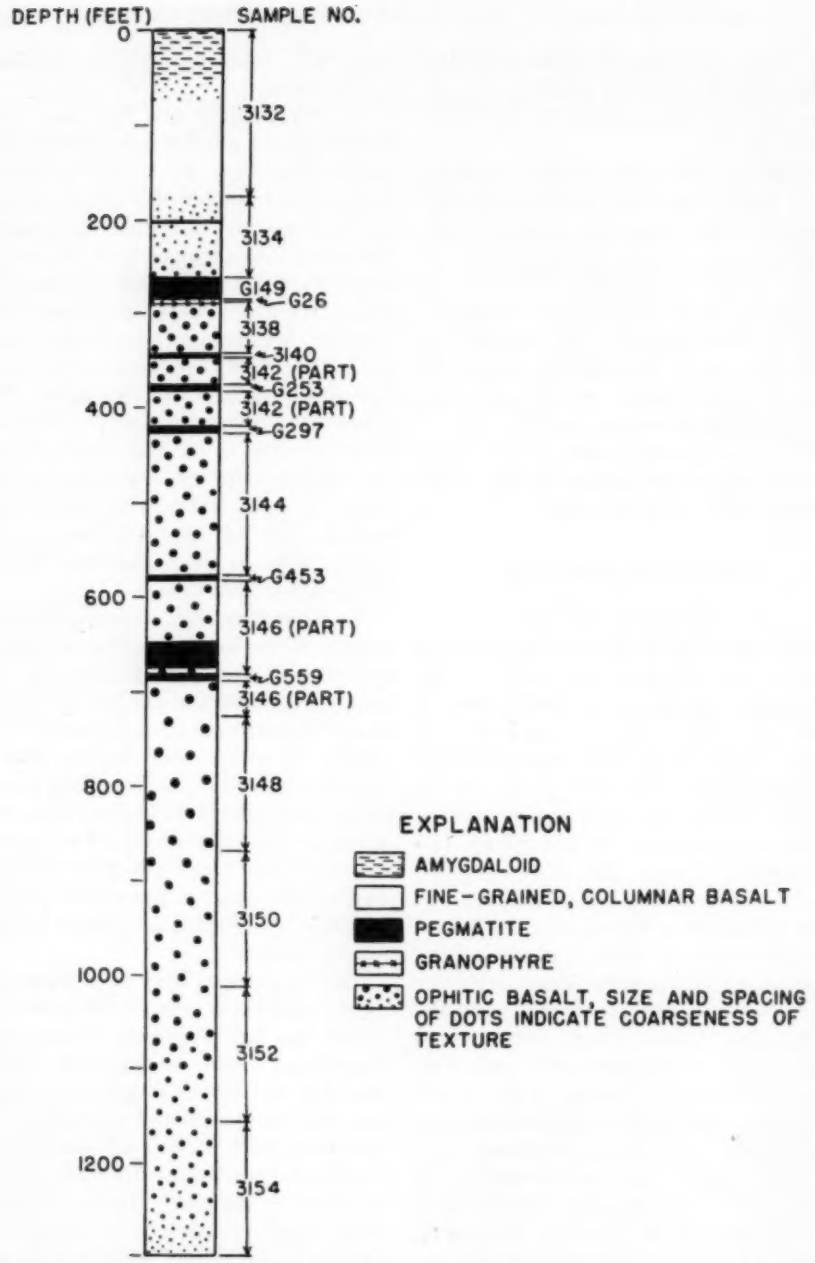

FIG. 1.—Columnar section of the Greenstone flow as exposed in three overlapping diamond-drill holes at Delaware, Michigan. Granophyre was not found in the diamond-drill core but was projected into the section on the basis of field data. Sample numbers indicate positions of analyses listed in table 1.

in the pegmatitic zone was different in the two hypotheses. During the later stages of crystallization, convection currents were assumed to have been active under hypothesis A, and the rocks solidified from bottom to top in the pegmatitic zone. Under hypothesis B it was assumed that there were no convection currents and that the rocks in the pegmatitic zone solidified from top to bottom. Magma trends have been computed for both hypotheses.

TABLE 2

VOLUMES OF ROCK USED TO COMPUTE SUCCESSIVE LIQUIDS DURING CRYSTALLIZATION OF GREENSTONE FLOW ACCORDING TO HYPOTHESIS A

Liquid	= Liquid +	Cubic Feet of Rock Sample	Rock Type
10		2	G26	Granophyre
9	10	23	G149	Pegmatitic layer
		56	3138	Basalt
8	9	4	3140	Pegmatitic layer
		28	3142	Basalt
7	8	7	G253	Pegmatitic layer
		37	3142	Basalt
6	7	7	G297	Pegmatitic layer
		150	3144	Basalt
5	6	5	G453	Pegmatitic layer
		100	3146	Basalt and pegmatitic facies
4	5	7	G559	Pegmatitic layer
		37	3146	Basalt and pegmatitic facies
		14	3148	Basalt
3	4	86	3134	Basalt
		130	3148	Basalt
		144	3150	Basalt
2	3	88	3132	Basalt
		144	3152	Basalt
1	2	88	3132	Basalt
		142	3154	Basalt
Total of flow		1,209		

MAGMA TRENDS UNDER HYPOTHESIS A

The order in which solid fractions were assumed to have crystallized from the magma of the Greenstone flow to yield successive liquids during solidification is shown in table 2. Although the writer calculated the successive liquids of the Greenstone flow in reverse order, that is, from the last to the first, he will discuss them below in the normal order of their occurrence.

At the time of liquid 4 the flow was 63 per cent solid. Up to this point crystallization of the upper chill zone and crystal accumulation at the base of the flow were going on simultaneously. Liquids 2, 3, and 4, therefore, were formed by the successive subtraction of solid fractions at both the top (analyses 3132 and 3134)

and the bottom (analyses 3154, 3152, 3150, and 3148) of the flow as shown in table 2. From liquid 4 to liquid 10, combined pairs of pegmatitic layers and subjacent basalt were successively subtracted, progressing from the bottom to the top of the pegmatitic zone. Liquid 10 was the residual liquid that solidified to form interstitial granophyre in the pegmatitic facies and granophyric dikes.

TABLE 3

COMPOSITION OF SUCCESSIVE LIQUIDS DURING CRYSTALLIZATION OF THE GREENSTONE FLOW ACCORDING TO HYPOTHESIS A

	Liquid									
	1	2	3	4	5	6	7	8	9	10
SiO_2	47.84	47.88	48.14	48.62	48.66	48.65	48.99	49.25	49.48	63.64
Al_2O_3	16.98	17.11	17.24	16.71	16.70	16.68	16.22	16.10	16.10	12.92
Fe_2O_3	3.18	3.17	3.29	3.30	3.50	3.82	3.78	3.85	3.87	3.18
FeO	7.92	7.94	7.91	8.19	8.14	7.95	8.37	8.44	8.46	2.80
MgO	6.73	6.46	5.77	5.07	4.96	4.74	4.61	4.50	4.38	1.77
CaO	10.01	10.01	9.96	9.50	9.47	9.65	9.13	8.84	8.50	6.01
Na_2O	2.63	2.69	2.85	3.20	3.22	3.16	3.33	3.30	3.27	3.37
K_2O	0.48	0.49	0.55	0.72	0.74	0.77	0.81	0.94	1.00	3.63
H_2O plus	2.23	2.24	2.17	2.18	2.15	2.00	2.00	2.05	2.00	1.50
CO_2	0.08	0.07	0.07	0.06	0.07	0.07	0.06	0.05	0.04	0.01
TiO_2	1.53	1.56	1.65	1.91	1.95	2.04	2.15	2.19	2.15	0.85
P_2O_5	0.18	0.19	0.20	0.23	0.23	0.25	0.26	0.28	0.29	0.17
S	0.026	0.023	0.019	0.020	0.020	0.019	0.020	0.023	0.026	0.02
Cu	0.012	0.013	0.013	0.015	0.015	0.016	0.015	0.015	0.017	0.007
MnO	0.168	0.168	0.170	0.178	0.178	0.180	0.177	0.183	0.177	0.11
Total	100.00	100.01	100.00	100.00	100.00	99.99	100.01	100.01	99.94	99.99
Total Fe as FeO	10.78	10.80	10.87	11.24	11.30	11.39	11.77	11.91	11.95	5.65
$\frac{TiO_2 \times 100}{FeO+Fe_2O_3+TiO_2}$	13.8	14.0	14.7	16.5	16.8	17.3	17.8	17.8	17.4	14.3
$\frac{Fe_2O_3 \times 100}{FeO+Fe_2O_3}$	28.6	28.5	29.4	29.3	30.0	32.5	31.1	31.3	31.4	53.1
$\frac{(FeO+Fe_2O_3) \times 100}{MgO+FeO+Fe_2O_3}$	62.3	63.3	66.0	69.5	70.2	71.3	72.5	73.2	73.9	77.2
Per cent solidified	0.0	17.6	35.5	63.1	67.6	75.8	87.8	91.2	93.7	99.85

In table 3 the compositions of the successive liquids are shown, and in figures 2 and 3 are plotted the composition trends of the constituents both in the magma and in the solid fractions that formed during crystallization. The SiO_2 and K_2O content of the magma increased very gradually during crystallization, with a marked increase in liquid 10. Na_2O increased gradually throughout. Total iron, as FeO, TiO_2, P_2O_5, MnO, and Cu, increased gradually to a peak when the flow was nearly solid and fell off sharply in the final liquid that crystallized to form granophyre. MgO, CaO, and Al_2O_3 decreased in amount in the magma during solidification.

Sulfur escaped from the magma and enriched the upper chill zone. Some sulfur probably escaped from the flow

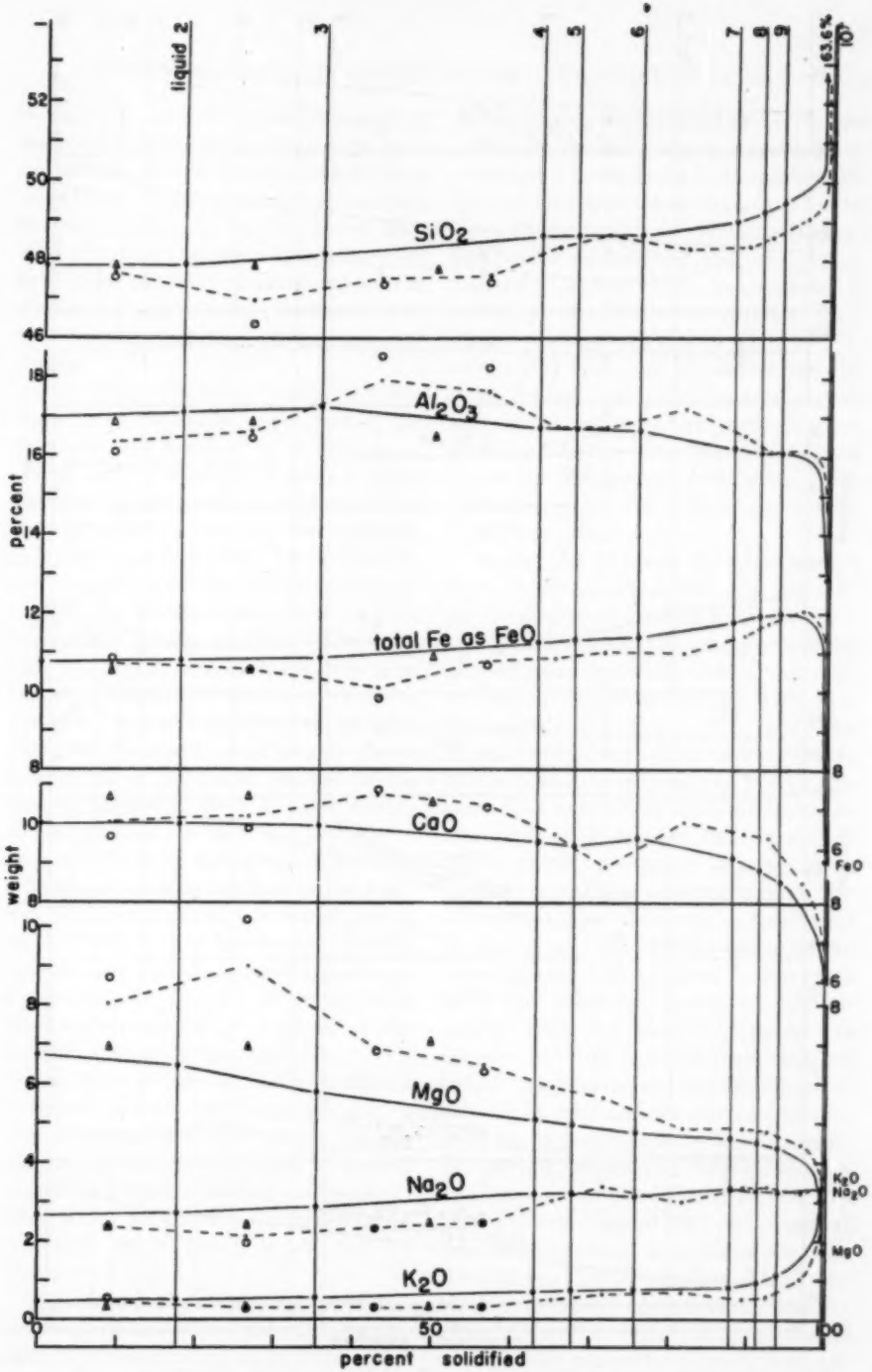

FIG. 2.—Composition trends of the magma and solid fractions during the crystallization of the Greenstone flow according to hypothesis A. Dots connected by solid lines indicate magma. Triangles indicate solid fractions from upper part of flow; eircles indicate solid fractions from lower part of flow; and dots connected by dashed lines are weighted averages of the solid fractions as combined in table 2.

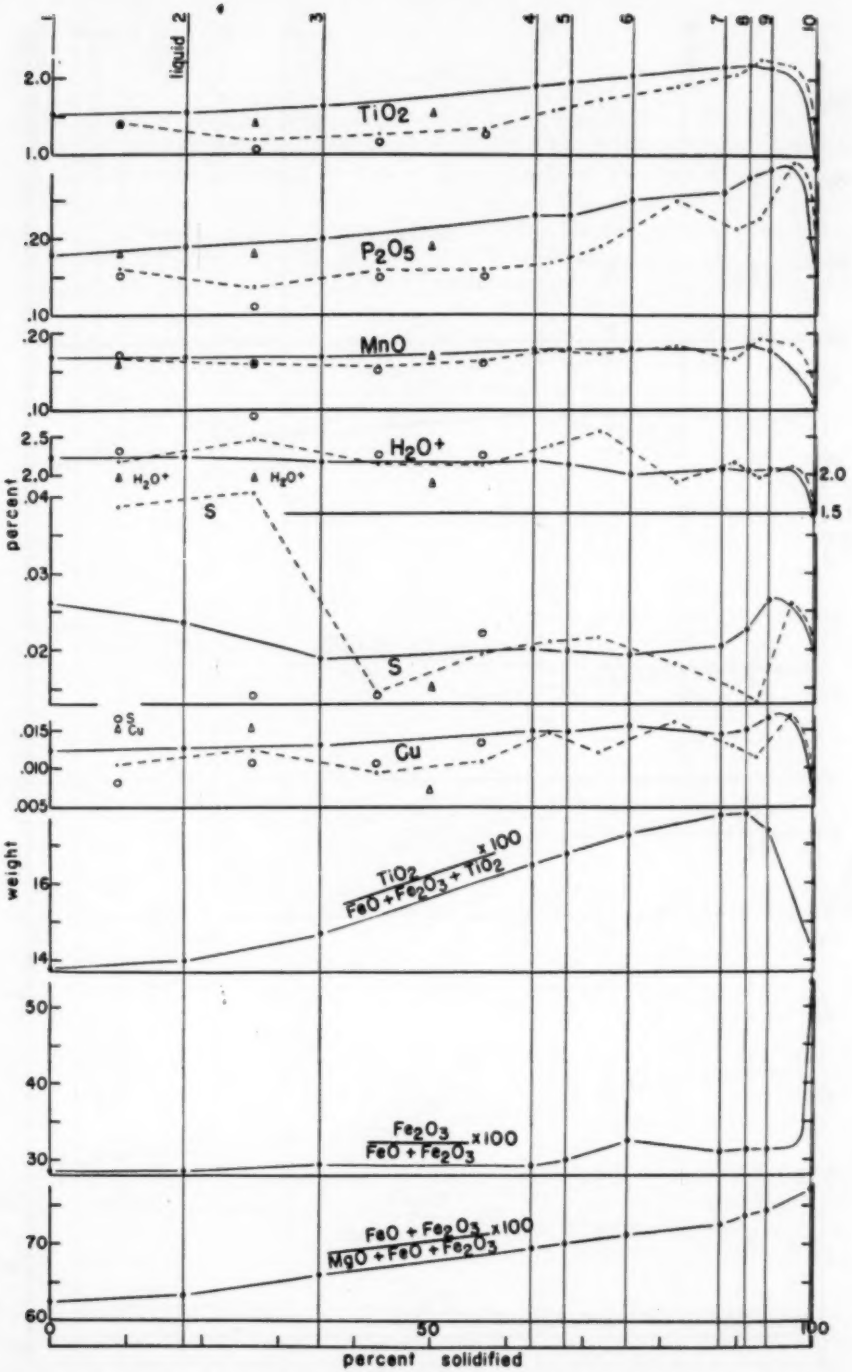

FIG. 3.—Composition trends of the magma and solid fractions during the crystallization of the Greenstone flow according to hypothesis A. Dots connected by solid lines indicate magma. Triangles indicate solid fractions from upper part of flow; circles indicate solid fractions from lower part of flow; and dots connected by dashed lines are weighted averages of the solid fractions as combined in table 2. Triangles for S omitted between liquids 1 and 2 and 2 and 3.

out of fumaroles. The upward migration and escape of sulfur were probably most rapid during the early stages of solidification. The evidence favoring this assertion has been presented by the writer elsewhere (1951*a*) and will not be discussed here. The sulfur that remained in the magma followed a trend similar to that of copper during the middle and late stages.

According to figure 3, combined water tends to be slightly less abundant in the fractions that solidified late. The analyses of individual units in table 1 show that combined water is most abundant in the pegmatitic facies and in the basalts of analyses 3146 and 3152. These two basalts are rich in olivine. As the olivine has been largely altered to serpentine and the pegmatitic phases contain abundant chlorite, epidote, and prehnite, it is to be expected that these parts of the flow would be rich in combined water. The curve of combined water merely shows how much of the water present in the magma combined with silicates during the crystallization and cooling of the flow and is not an indication of the total amount of water in solution in the magma. This total amount of water during crystallization was determined by the temperature and the confining pressure; a considerable amount of water must have boiled out of the magma as the anhydrous minerals crystallized.

The ratio of iron oxides to magnesia increased steadily in the magma during crystallization, and there was a gradual increase in the ratio of ferric to ferrous iron, with a marked increase in liquid 10. The ratio of TiO_2 to iron oxides increased markedly up to liquid 8 and fell off sharply in liquid 10.

The correctness of the values of the ratios discussed above depends on the validity of the assumption that the ratios in the magma were related directly to the ratios in the solid fractions. In other words, if a given ratio in a certain fraction of rock was lower than that of the liquid from which it crystallized, that ratio in the succeeding liquid was proportionately higher. This assumption is probably correct for the ratios of iron oxides to magnesia and of TiO_2 to iron oxides but may not be correct for the ferric-ferrous iron ratio because it was affected not only by the proportions of ferric and ferrous iron that crystallized out of the magma but also by the equilibrium between the magma and the O_2 in the vapor phase.

In the case of lavas the ferric-ferrous ratio of the solidified flow also depends on the degree of oxidation of the iron-bearing minerals in the solid parts of the flow by gases that boiled out of the magma during crystallization. This problem is discussed further on pages 167–169. The writer (1951*b*) has found, however, that the iron-bearing minerals of the Greenstone flow were not oxidized in this manner except in the top few feet of the flow.

The oxidizing effect of escaping gases on the crystallized iron minerals in the Greenstone flow, then, was so small that it can be ignored, but the effect of the vapor phase on the magma before crystallization must be considered. Experimental work by Kennedy (1948) has shown that the ferric-ferrous ratio of basaltic magma depends on the temperature of the melt and the partial pressure of O_2 vapor in equilibrium with the melt. The partial pressure of O_2 depends on the total pressure of the volatiles and the degree of dissociation of H_2O, the principal volatile constituent in equilibrium with the magma. The dissociation of H_2O into H_2^+ and O^- is proportional to the temperature. Kennedy's (1948) data, as shown elsewhere by the writer (1951*b*), indicate

that the decrease of dissociation of H_2O for a given temperature drop with constant total volatile pressure is more than offset by the increased oxidizing effect of O^- on iron at the lower temperature, so that the net effect of a drop in temperature, the pressure remaining constant, is an increase in the ferric-ferrous ratio of the melt.

From the time the lava of the Greenstone flow was extruded, the total volatile pressure probably exceeded the confining pressure and gave rise to bubbles. Thus volatile pressure became and remained equal to confining pressure. As the confining pressure stayed nearly constant throughout solidification at any given level and the temperature decreased very slowly, the ferric-ferrous ratio of the magma increased slowly as the temperature decreased.

Inequilibrium in the magma of the ferric-ferrous ratio, as in the case of liquid 6 discussed below, probably occurred at times because of a change in the respective rates of crystallization of the iron-bearing minerals (olivine, pyroxene, magnetite, and ilmenite); but equilibrium would tend to be re-established by the reduction or oxidation of iron in the magma. The residual liquid must have crystallized to form granophyre at a considerably lower temperature than the rest of the magma, because of its alkalic nature and the presence of volatiles, and therefore had a much higher ferric-ferrous ratio.

The rock that formed from liquid 5 (plotted halfway between liquids 5 and 6 in figs. 2 and 3) was unique among the solid differentiates of the flow, in that its SiO_2 content equaled that of the liquid, the Na_2O content was higher, and the CaO content lower. The basalt that forms the bulk of this rock is also unique mineralogically. It contains much more olivine and a more sodic plagioclase than did the rock that crystallized earlier or later. The ferric-ferrous ratio of the magma (i.e., in liquid 6) was temporarily increased by the crystallization of the olivine-rich rock. This rock contains an abnormal concentration of minerals rich in FeO. Equilibrium between ferric and ferrous iron was probably re-established by the time of liquid 7. The olivine-rich rock has a higher-than-normal SiO_2 content for rock crystallizing at that stage because the most abundant constituent of the rock is a more sodic plagioclase that required an increased proportion of SiO_2 in its formation.

There is a threefold increase in the amount of K_2O from liquids 9–10, whereas the Na_2O content is nearly constant. Thus a basalt magma that originally contained five and a half times as much soda as potash produced, by differentiation, a residual magma that contained slightly more potash than soda.

MAGMA TRENDS UNDER HYPOTHESIS B

The manner in which solid fractions were subtracted from the magma of the Greenstone flow, according to hypothesis B, is shown in table 4, and the compositions of the successive liquids are shown in table 5. Successive solid fractions inward from the top and bottom were simultaneously subtracted from the magma according to the manner in which it was assumed that the flow solidified. By the time of liquid 7 it was assumed that the magma contained sufficient crystals to inhibit completely further crystal settling. The remaining magma solidified from the top down because cooling was predominantly from the top. Liquid 9 was the residual liquid, equivalent to liquid 10 in hypothesis A.

The compositions of the successive liquids and the solid fractions forming

therefrom are shown in figures 4 and 5. The amounts of most of the constituents in the magma remained nearly constant throughout the solidification up to liquid 8. In the absence of convection currents a composition gradient was gradually established in the magma by transfer upward of the more volatile constituents (Fe, Mn, Ti, Cu, S, P, Si, K, Na) by escaping gases. Fractions of magma that crystallized at the top of the flow to form the upper chill zone were relatively rich in the more volatile elements, whereas crystals settling to the base were relatively rich in Mg and Ca. The average composition of the whole magma column tended to remain constant.

Certain trends are apparent in the successive liquids, however, despite the tendency for the upper and lower parts of the magma column to compensate each other. In general, the more volatile constituents, particularly SiO_2 and Na_2O, increased gradually; MgO and CaO decreased; and Al_2O_3 declined in the later stages. Sulfur bubbled out of the magma, particularly during the early stages (see discussion, pp. 156–159), and enriched the upper chill zone. The amount of combined water remained constant through

TABLE 4

VOLUMES OF ROCK USED TO COMPUTE SUCCESSIVE LIQUIDS DURING CRYSTALLIZATION OF GREENSTONE FLOW ACCORDING TO HYPOTHESIS B

Liquid	= Liquid +	Cubic Feet of Rock	Sample	Rock Type
9		2	G26	Granophyre
8	9	7	G559	Pegmatitic layer
		37	3146	Basalt and pegmatitic facies
7	8	5	G453	Pegmatitic layer
		100	3146	Basalt and pegmatitic facies
6	7	7	G297	Pegmatitic layer
		150	3144	Basalt
		94	3148	Basalt
5	6	7	G253	Pegmatitic layer
		37	3142	Basalt
		50	3148	Basalt
4	5	4	3140	Pegmatitic layer
		28	3142	Basalt
		43	3150	Basalt
3	4	23	G149	Pegmatitic layer
		56	3138	Basalt
		101	3150	Basalt
2	3	86	3134	Basalt
		144	3152	Basalt
1	2	176	3132	Basalt
		142	3154	Basalt
Total of flow		1,299		

liquid 6 and was higher in liquids 7 and 8. The basalt that formed from liquids 7 and 8 is rich in olivine, and the olivine has been largely altered to hydrous serpentine. Thus the high content of combined water of liquids 7 and 8 merely indicates that the rocks derived from them were rich in serpentine. The significance of the combined-water curve has been discussed on page 159.

The ratio of iron oxides to magnesia increased abruptly in liquid 3 and remained constant thereafter to liquid 8. The ratio of TiO_2 to iron oxides increased from liquid 1 to liquid 8. The ratio of ferric to ferrous iron remained constant to liquid 6 and fell off abruptly in liquids 7 and 8. The lower value of the ferric-ferrous ratio in liquids 7 and 8 appears anomalous and might indicate that the assumption made under hypothesis B, that the rock near the middle of the flow solidified last, is not valid. As pointed out on pages 159–160, however, the ferric-ferrous ratio of the magma was dependent on other factors besides the ferric-ferrous ratio of the solid fractions that crystallized from the magma. The true values of this ratio in liquids 7 and 8 could, therefore, have been higher than those shown in table 5 and figure 5.

From liquid 8 to liquid 9 under hy-

TABLE 5

COMPOSITION OF SUCCESSIVE LIQUIDS DURING CRYSTALLIZATION OF THE GREENSTONE FLOW ACCORDING TO HYPOTHESIS B

	Liquid								
	1	2	3	4	5	6	7	8	9
SiO_2	47.84	47.88	48.18	48.19	48.23	48.31	48.84	49.25	63.64
Al_2O_3	16.98	17.13	17.32	17.27	17.24	17.19	16.58	16.22	12.92
Fe_2O_3	3.18	3.08	3.14	3.15	3.17	3.15	2.55	2.52	3.18
FeO	7.92	8.04	8.05	8.05	8.06	8.06	8.63	8.50	2.80
MgO	6.73	6.42	5.62	5.56	5.50	5.47	5.61	5.58	1.77
CaO	10.01	9.95	9.90	9.93	9.87	9.81	9.06	9.36	6.01
Na_2O	2.63	2.72	2.90	2.95	2.98	3.00	3.37	3.30	3.37
K_2O	0.48	0.50	0.57	0.55	0.57	0.62	0.68	0.72	3.03
H_2O plus	2.23	2.26	2.20	2.21	2.22	2.22	2.55	2.48	1.50
CO_2	0.08	0.07	0.07	0.07	0.07	0.07	0.06	0.05	0.01
TiO_2	1.53	1.57	1.66	1.67	1.68	1.69	1.70	1.69	0.85
P_2O_5	0.18	0.19	0.20	0.20	0.20	0.20	0.18	0.17	0.17
S	0.026	0.018	0.019	0.019	0.020	0.020	0.021	0.021	0.02
Cu	0.012	0.013	0.014	0.014	0.014	0.015	0.013	0.015	0.007
MnO	0.168	0.169	0.170	0.171	0.172	0.174	0.173	0.169	0.11
Total	100.00	100.01	100.01	100.00	99.99	99.99	100.01	100.05	99.99
Total Fe as FeO	10.78	10.82	10.87	10.89	10.92	10.90	10.93	10.72	5.65
$\frac{TiO_2 \times 100}{FeO+Fe_2O_3+TiO_2}$	13.8	14.1	14.8	14.9	14.9	15.1	15.2	15.3	14.3
$\frac{Fe_2O_3 \times 100}{FeO+Fe_2O_3}$	28.6	27.7	28.0	28.2	28.2	28.1	22.8	22.8	53.1
$\frac{(FeO+Fe_2O_3) \times 100}{MgO+FeO+Fe_2O_3}$	62.3	63.4	66.6	66.9	67.1	67.2	66.6	66.4	77.2
Per cent solidified	0.0	24.3	42.1	56.0	61.8	69.1	88.3	96.4	99.85

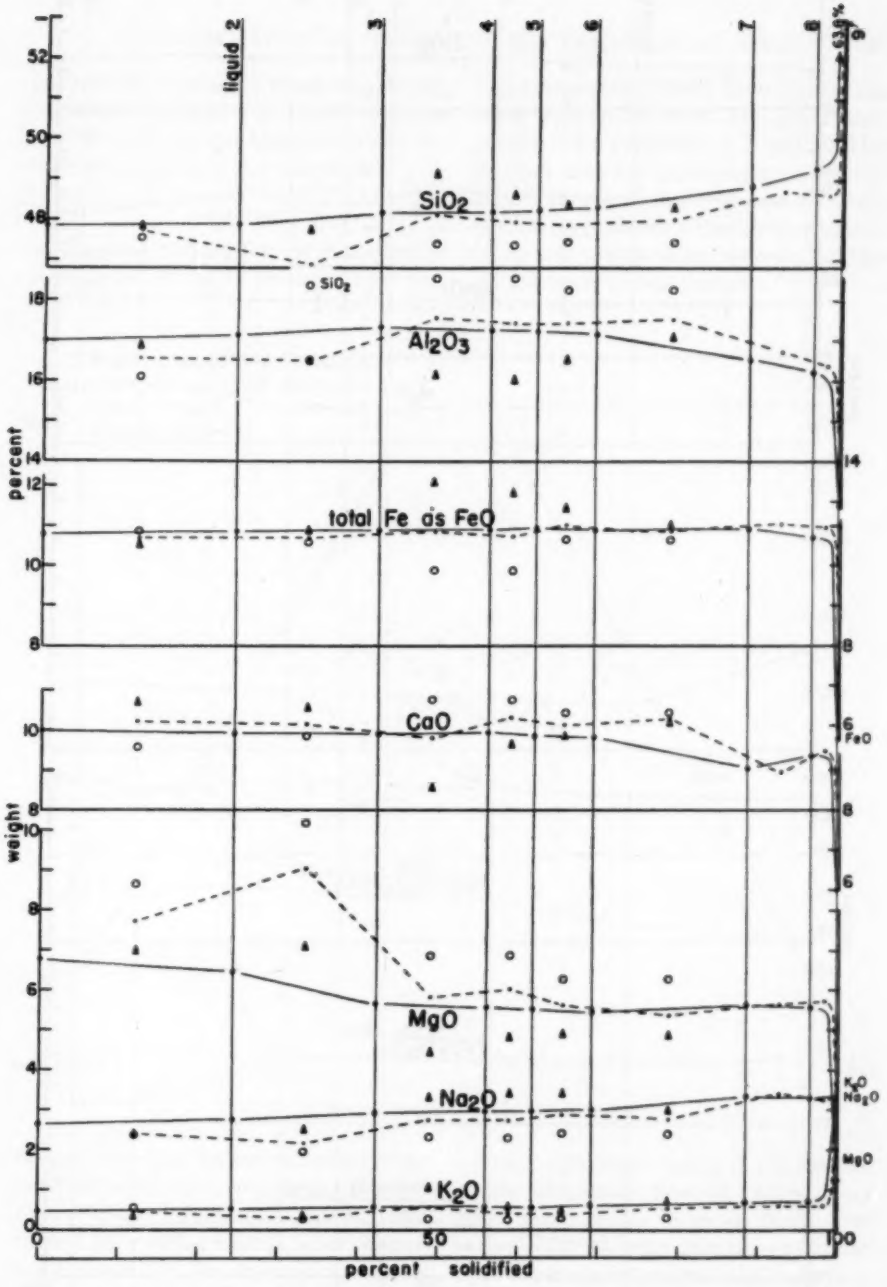

FIG. 4.—Composition trends of the magma and solid fractions during the crystallization of the Greenstone flow according to hypothesis B. Dots connected by solid lines indicate magma. Triangles indicate solid fractions from upper part of flow; circles indicate solid fractions from lower part of flow; and dots connected by dashed lines are weighted averages of the solid fractions as combined in table 4.

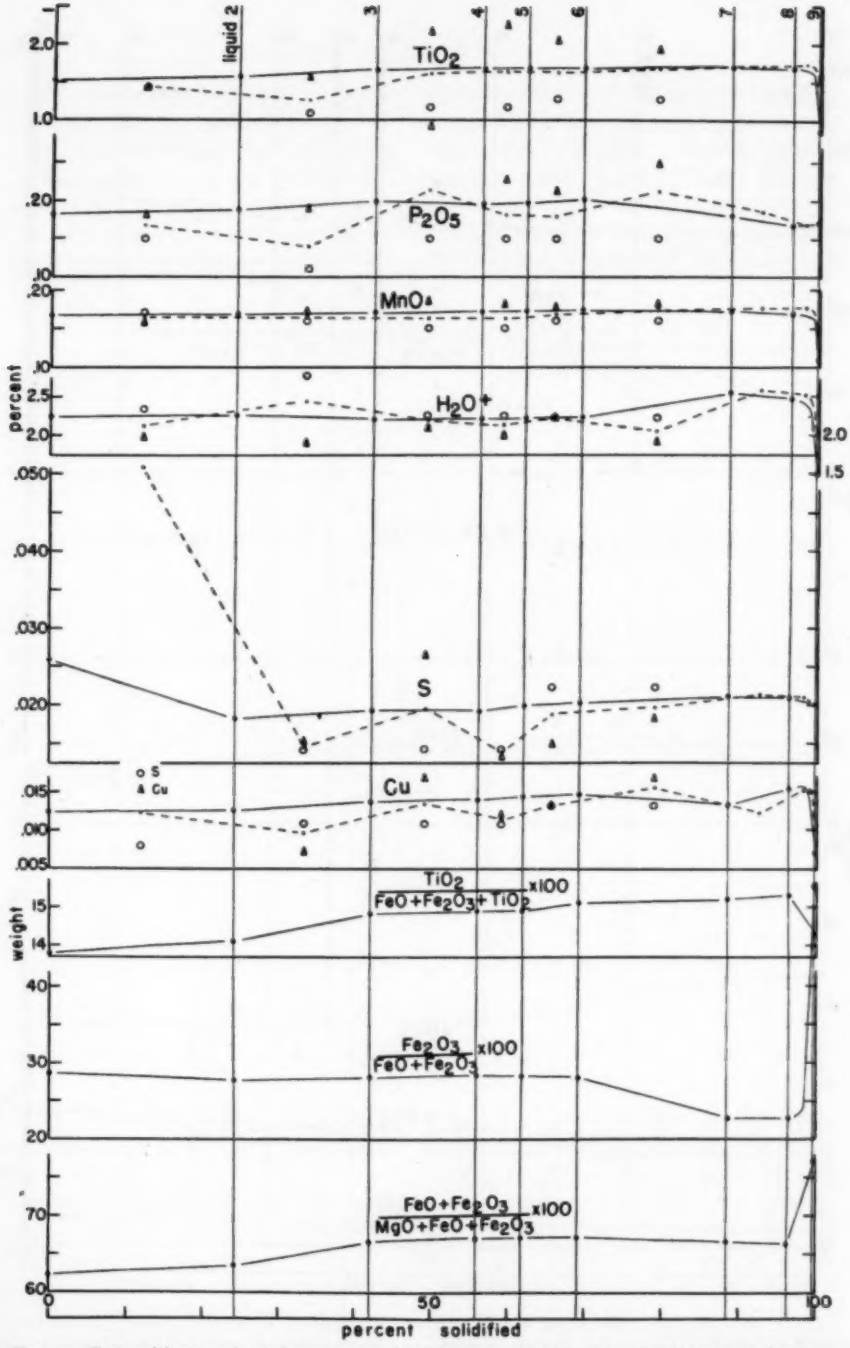

FIG. 5.—Composition trends of the magma and solid fractions during the crystallization of the Greenstone flow according to hypothesis B. Dots connected by solid lines indicate magma. Triangles indicate solid fractions from upper part of flow; circles indicate solid fractions from lower part of flow; and dots connected by dashed lines are weighted averages of the solid fractions as combined in table 4. Triangle for S omitted between liquids 1 and 2.

pothesis B the magma trend was similar to that from liquid 9 to liquid 10 under hypothesis A, except that P_2O_5 and S remained constant in hypothesis B.

SUMMARY

The most striking feature of the basaltic magma of the Greenstone flow was the residual liquid that remained after the flow had almost completely solidified. This residual liquid was strongly contrasted with earlier liquids in its composition, especially by its high content of silica and potash, and must have crystallized to form granophyre at a temperature considerably lower than that of the main body of the flow. The lower temperature of crystallization is indicated by the fact that the granophyre commonly occurs in dikes that intrude the pegmatitic zone, showing that the pegmatitic facies and ophitic basalt were solid when the granophyre was liquid.

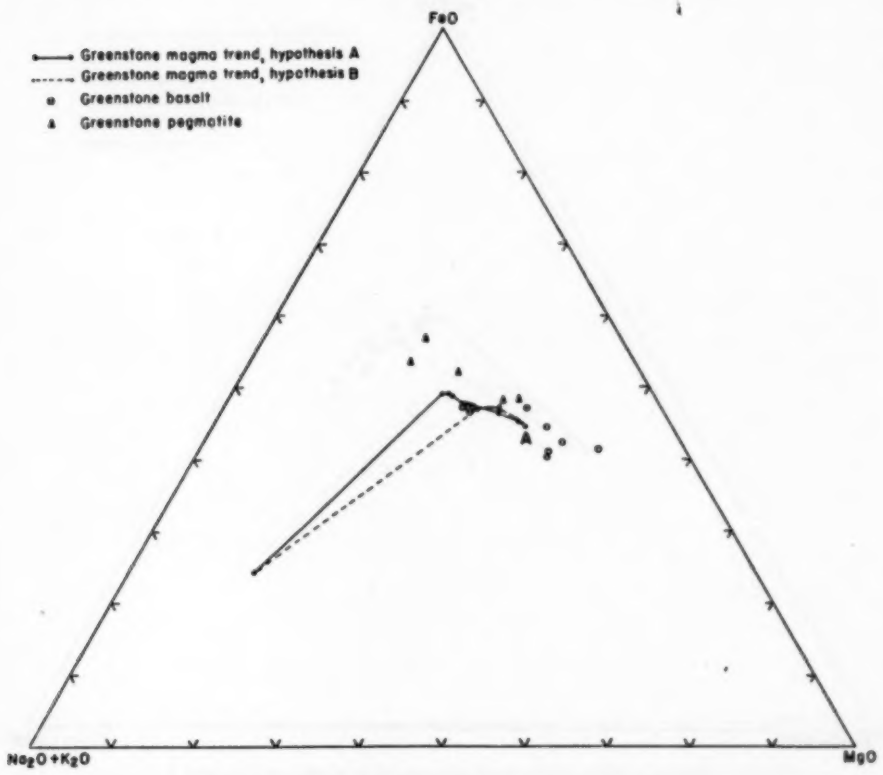

FIG. 6.—Differentiation trend of the Greenstone flow

Other significant trends in the magma of the Greenstone flow, in general most pronounced under hypothesis A, are: early escape of large quantities of sulfur from the magma; peaks in the content of Fe, Ti, P, Mn, S, and Cu when the flow was nearly solid; gradual increase in Na

and decrease in Mg and Ca throughout solidification; decrease in Al after the early stages of solidification.

Trends in the differentiation of basaltic magma can be shown by plotting the compositions of the successive liquids with respect to MgO, FeO, and total alkalies (Na_2O plus K_2O) on a triangular diagram. Wager and Deer (1939, pp. 313–315) and Walker and Poldervaart (1949, pp. 657–661) have plotted representative suites of basalts, diabases, and gabbros from different parts of the world in this manner. A similar diagram of the magma of the Greenstone flow is shown in figure 6; and, in addition, the individual analyses of solid fractions have also been plotted. The original magma had the composition of point *A*, and later liquids were successively enriched in FeO and alkalies with respect to MgO up to, but not including, the final liquid from which the granophyre crystallized. The final liquid was markedly enriched in alkalies with respect to both MgO and FeO. The solid fractions follow a trend similar to that for the magma, but the range in composition is greater; the early solid fractions are richer in MgO, and the later solid fractions are richer in FeO, than the magma under either hypothesis A or hypothesis B.

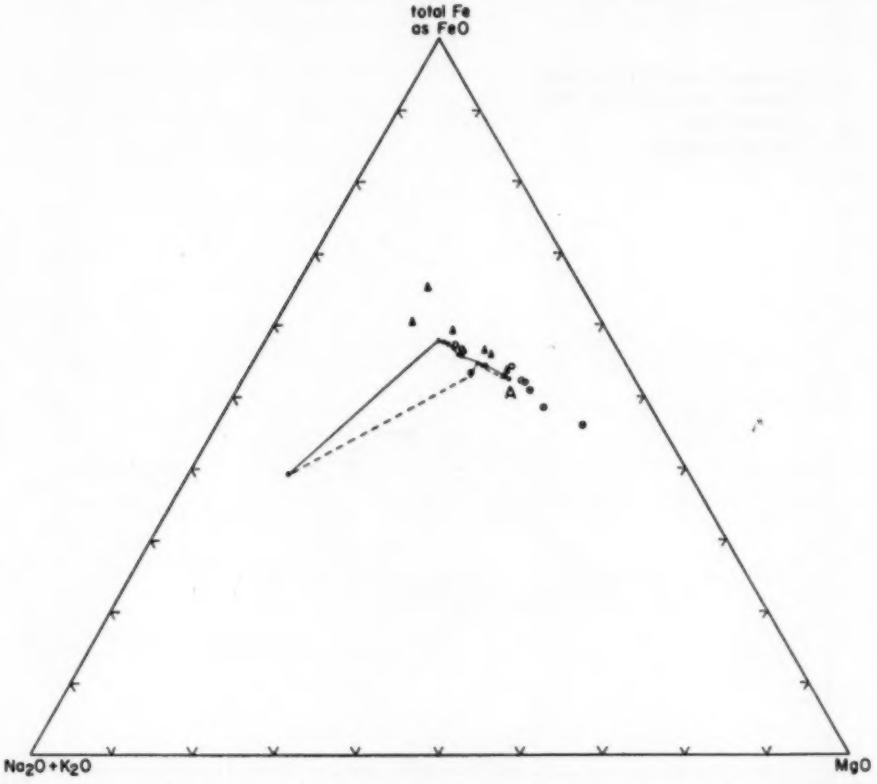

FIG. 7.—Differentiation trend of the Greenstone flow. Explanation same as for figure 6

In figure 7 total Fe as FeO was substituted for FeO as one apex of the triangular diagram. The relations in figure 7 are similar to those in figure 6. The differentiation trends in the magma of the Greenstone flow were typical for those of basaltic magma in general, as can be seen by a comparison of figure 6 with similar diagrams of Walker and Poldervaart (1949, pp. 657–661).

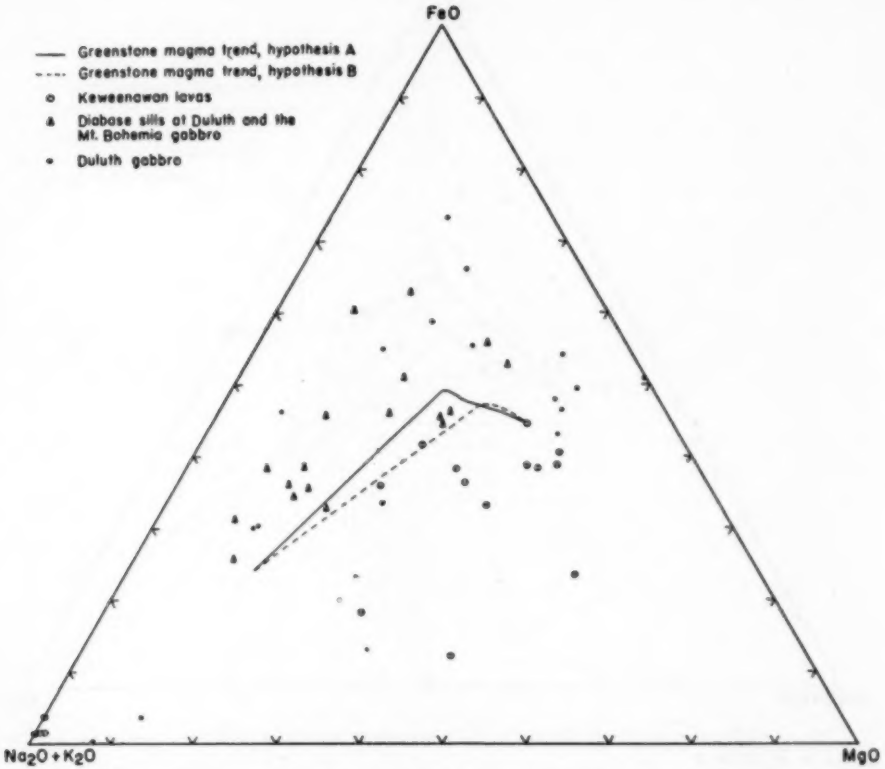

FIG. 8.—Differentiation trends of lavas of the Keweenawan series and related intrusives

TRENDS IN KEWEENAWAN MAGMAS

In figure 8 analyses of gabbros, diabases, and lavas of the Keweenawan series of the Lake Superior region have been plotted according to their relative contents of MgO, FeO, and alkalies. For the gabbros and diabases each analysis represents a solid differentiate of the magma. Each lava analysis is of a composite sample of a single flow and thus represents original magma minus escaped volatiles. The analyses of Duluth gabbro are from Grout (1918, pp. 646–650); those of the diabase sills at Duluth are from Schwartz and Sandberg (1940, p. 1144); and those of the lavas and gabbro of Mount Bohemia are from Broderick (1935, pp. 511–537). The trends of the magma of the Greenstone flow are also shown in figure 8.

Several of the lavas are abnormally

deficient in FeO with respect to MgO and total alkalies. The writer (1951*b*) in a study of the relations of magnetite, ilmenite, and hematite in the lavas of the Keweenawan series has found that the 9. The lavas have a more uniform distribution in figure 9 than in figure 8, whereas the relations of the intrusives and the magma of the Greenstone flow are not greatly changed.

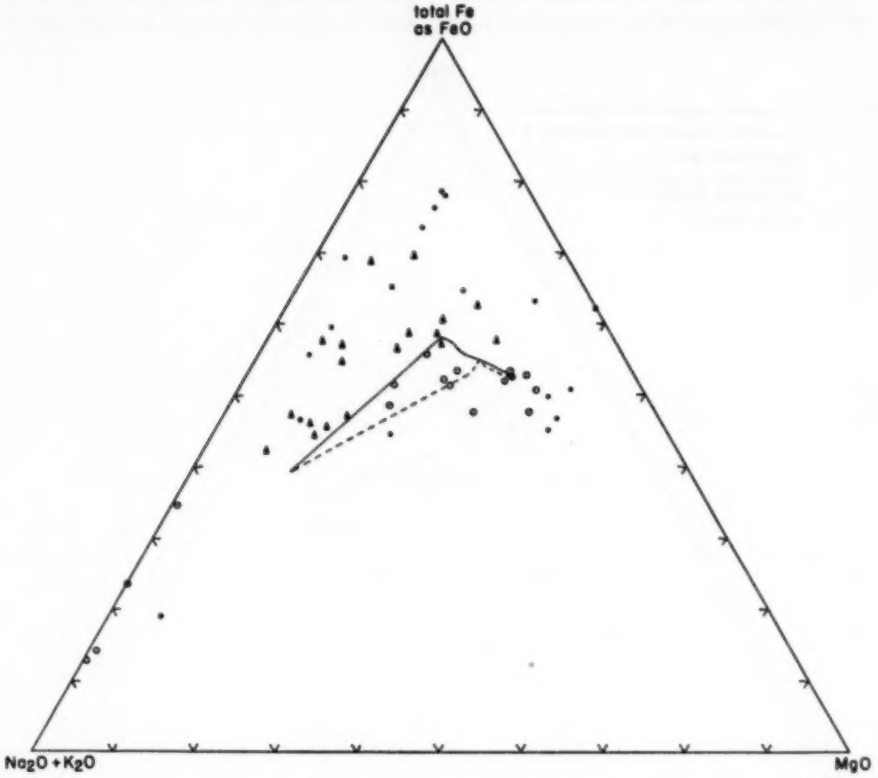

FIG. 9.—Differentiation trends of lavas of the Keweenawan series and related intrusives. Explanation same as for figure 8.

FeO in iron-bearing minerals has been slightly to intensely oxidized by gases that boiled out of the flows during crystallization. Thus the FeO content of solid lava is not necessarily related to the original FeO content of the magma. Therefore, the writer has substituted total Fe, calculated as FeO, for FeO in the ternary diagram and plotted the results in figure

The fact that iron tends to be more oxidized in extrusive than in intrusive basaltic rocks has also been observed by Walker and Poldervaart (1949, p. 648), who state:

> The almost exact correspondence of the Karroo dolerites with the Stromberg lavas is to be expected and finds counterparts in other provinces—e.g., the close chemical resemblance

of the chilled Palisade diabase to the Watchung traps. In both cases the iron is more oxidized in the effusive phase, where the escape of gas is accelerated; this agrees with the conclusions of Phemister (1934, pp. 40–44).

The magma trends in the Duluth gabbro, the diabase sills at Duluth, the lava extrusives, and the Greenstone flow have been drawn in figure 10. The trend of the lava extrusives is a median line drawn through the points shown as circles in figure 9. The magma trends of the Duluth gabbro and sills were estimated from the compositions of the solid fractions, shown by dots and triangles in figure 9, by analogy with the known relationships of the Greenstone flow and consideration of the experimental data of Bowen and Schairer (1935) on the system MgO-FeO-SiO_2. These data indicate that during crystallization the composition range of a magma is less extreme than that of its differentiation products. Considered in terms of the ternary diagram (figs. 7, 9, 10), early crystallization products are somewhat more magnesian than the magma from which they formed; later crystallization products are somewhat richer in iron oxides than the magma.

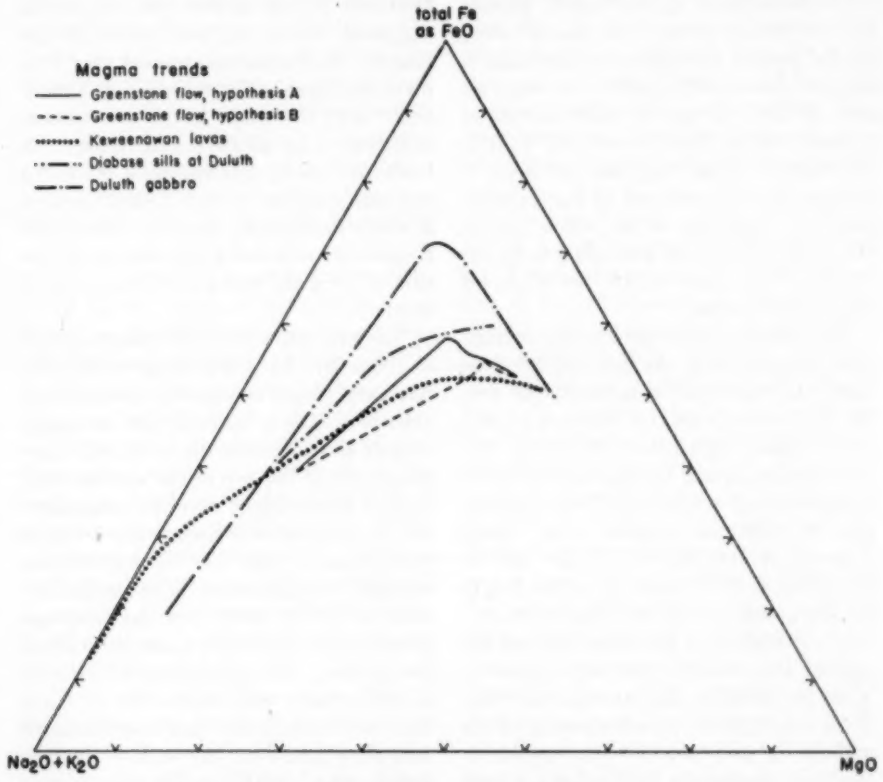

FIG. 10.—Differentiation trends of magmas of the Keweenawan series

Changes in the compositions of mag-

mas were dependent on the original composition and the degree of differentiation during crystallization and extrusion. Our knowledge of the Greenstone flow and the Duluth gabbro indicates that fractional crystallization was the most important factor in the differentiation of these bodies. The differentiation was more pronounced in the Duluth gabbro than in the Greenstone flow, as evidenced by the greater enrichment of the magma in iron oxides with respect to magnesia and alkalies during the main period of crystallization. Both produced, by differentiation, small residual fractions of magma that crystallized to form granophyre, 0.15 per cent of the whole for the Greenstone flow and, according to Grout (1918, p. 639), 2 per cent of the whole for the Duluth gabbro.

The diabase sills at Duluth formed from magma that corresponds to partially differentiated magma of the Duluth gabbro, as indicated in figure 10, and are probably offshoots of that body. Differentiation during crystallization in the sills produced a relatively large proportion of residual magma from which granophyre crystallized, 25 per cent of the whole in the Endion sill, according to Schwartz and Sandberg (1940, p. 1141). This substantiates the inference that the magma was already partly differentiated when intruded, as does also the fact that there was little or no enrichment of the magma in iron oxides with respect to magnesia during the early stages of crystallization. Analyses of typical diabase from the sills at Duluth show that, in addition to having a higher iron-oxides-to-magnesia ratio than the Duluth gabbro and the basalt of the Greenstone flow, they also contain more TiO_2 and P_2O_5. Incomplete data also indicate that they contain more Cu.

The most mafic lavas had a composition close to that of the original magma of the Duluth gabbro, and it may be inferred that the lavas and gabbro were derived from the same parent-magma but that the courses of differentiation were different. Conditions of crystallization in the Duluth gabbro permitted strong differentiation, as shown by a marked enrichment in iron oxides with respect to magnesia during crystallization of the magma. In the parent-magma that supplied the lavas, differentiation was moderate, and the main trend was toward enrichment in alkalies with respect to both iron oxides and magnesia. As in the residual magmas of the Duluth gabbro and the Greenstone flow, the alkali-rich lavas also contained a marked concentration of silica and had a rhyolitic composition.

Rhyolite plus rhyolitic conglomerate (formed by the weathering of rhyolite flows and plugs) constitutes about 20 per cent of the lava series in the Michigan copper district if the thick rhyolitic conglomerate at the top of the section is included. If the upper rhyolitic conglomerate is excluded, the lava series contains only about 0.5 per cent of rhyolite plus rhyolitic conglomerate. The conglomerates occur at fairly regular intervals about 1,000–1,500 feet apart throughout the section. The rhyolites and rhyolitic conglomerates are contrasted in their composition with the basalts and basaltic andesites that form the bulk of the lava series, just as the minor amounts of granophyre and red rock in the Greenstone flow and Duluth gabbro are contrasted in composition with the predominant basalt and gabbro, respectively, in these bodies.

The magma that supplied the lavas probably occupied a chamber or chambers at great depth, because it remained liquid for a long period and the undiffer-

entiated basaltic lava contained few intra-telluric crystals when extruded. Differentiation of basaltic magma by fractional crystallization under conditions of slow cooling would probably have produced a trend similar to that shown for the lavas in figure 10. We are confronted, however, with the problem of the more or less cyclic repetition of the several types of lava from the bottom to the top of the series. A typical cycle, as suggested by Broderick (1935, p. 554), progresses from basalt to andesite to rhyolitic conglomerate and typically includes about 1,000–1,500 feet of the lava section that has a total thickness of about 20,000 feet.

Repeated flow cycles in the lava series are difficult to explain under any theory of differentiation. A possible explanation, based on the theory of differentiation of basaltic magma by fractional crystallization, has been suggested to the writer by Buddington.[2] He proposes that each set of lavas, constituting one flow cycle, corresponds to a subperiod of magma rise. Part of the magma comes directly to the surface to form basalt flows, while part stops one or more times en route to the surface and differentiates by fractional crystallization. Some of the magma is differentiated to the extent that it yields rhyolitic magma, that is, in turn, extruded to the surface.

The cyclic repetition of contrasted types of lava in the series might also be explained by assuming that the parent-magma was differentiated in the liquid phase in the magma chamber with little crystallization. Two hypotheses based on this assumption have been proposed by Fenner (1948) and Wahl (1946), respectively. Fenner (1948) suggests that, for a certain temperature range above the freezing point of basalt magma, basalt and rhyolite magmas are immiscible and that magmas ranging in composition between the two extremes are produced by mixing of varying amounts of the two types. Wahl (1946) proposes that differentiation may occur in a body of magma because of thermal diffusion-convection in the liquid phase. The above hypotheses may be valid, but no evidence has been derived from the present study that supports either of them. Evidence has been presented, however, that the magmas studied were differentiated by fractional crystallization, and we may logically conclude that fractional crystallization was the primary cause of differentiation.

In considering the origin of the lavas of the Lake Superior region, we must also include the possibility of the production of hybrid magmas by the assimilation of sialic material from the walls of a deep-seated basaltic magma chamber. The differentiation trends in the lavas of the Lake Superior region approach the line of descent of the calc-alkaline suite represented by Daly's (1933, pp. 9–17) average basalt, andesite, dacite, and rhyolite. A number of petrologists, including Wager and Deer (1939, p. 335) and Edwards (1942, p. 609), believe that the calc-alkaline series formed by the assimilation by basaltic magma of sialic material, whereas Walker and Poldervaart (1949, p. 661) "consider it likely that the calc-alkaline suite may be produced by fractionation of basalt magma, though they do not exclude the possibility of assimilation of sialic material, followed by crystallization-differentiation of the hybrid magma."

[2] Personal communication.

SUMMARY

Differentiation by fractional crystallization of basaltic magma in intrusives and extrusives of the Keweenawan series of the Lake Superior region caused en-

richment of the magma first in iron oxides with respect to magnesia and finally in alkalies and silica. In the formation of the lava series the degree to which basaltic magma assimilated sialic material is not known. The available data, however, do indicate a similarity between the magma trend in the lava series as a whole and that found within the Greenstone flow, and the magma trend within the Greenstone flow is known to have been established by the differentiation of a basaltic magma. Confronted, on the one hand, with a complete lack of information on the importance of assimilation and, on the other, with proof of the adequacy of magmatic differentiation to produce the types of lava found in the Lake Superior region, we may tentatively conclude that the lavas originated by the differentiation of basaltic magma, modified to an unknown extent by the assimilation of sialic material.

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Officials of Calumet and Hecla kindly granted permission to study and collect samples of the Greenstone flow from their diamond-drill core. Eleven of the chemical analyses used in the study of the Greenstone flow were obtained by Dr. Broderick. Six analyses were financed by a grant from Princeton University.

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GEOLOGICAL NOTES

THE GEOLOGICAL WORK OF THE MOUND-BUILDING ANTS IN WESTERN UNITED STATES[1]

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Numerous barren patches with conical mounds of earth are scattered throughout most of the Great Plains and in the intermontane basins of the Rocky Mountains. Locally they are so abundant that they form the most obvious physiographic feature in the area. They stand out as prominent breaks in the grassland or low sagebrush areas and are often mistaken by the traveler for prairie-dog "towns" or gopher dens. Such mounds have been built by ants, and the scope of their work indicates that they are the most active animal, other than man, engaged in the transportation of soil in the semiarid regions of portions of the western half of the United States.

The low cone-shaped hills of the mound-building ants may be the most obvious landscape feature of some areas. From an elevation a few feet above the surrounding mound-covered flat, a few hundred of the circular clearings with their central mounds may be observed (pl. 1, *C*). While flying at low altitude over such routes as that between Riverton and Casper, Wyoming, an observer can see thousands of the clearings and will recognize them as the most abundant and perhaps most striking physiographic features in the area.

They can be observed on aerial photographs as circular, white to gray dots (pl. 2). These dots show in sagebrush-covered areas as well as on barren surfaces, because the ants do not allow vegetation to grow within the clearing. Examples of aerial photographs which show mounds in abundance are BBN-60-3246, 3247, 3249, 3250, 3258, 3259, Bighorn County, Wyoming; CWH-2B-128, 129, 130, 190, Hot Springs County, Wyoming; CVT-2B-37, 38, 39, Uinta County, Wyoming; and CVP-4B-36, 37, 38, 39, 40, Arco Area, Butte County, Idaho; all photos by U.S. Department of Agriculture.

Entomologists (Headlee and Dean, 1908; Wheeler, 1910) are well acquainted with the work of the mound-building ants. They have identified several species of *Pogonomyrmex* and *Formica* as common mound-builders. The purpose of this paper is to call to the attention of geologists the importance of this group of organisms in the construction of landscape features and the amount of rock handled.

The mound-building ants are known to range over an extensive area. The writer has observed them as far south as the Mexican Plateau near San Luis Potosí and as far north as Montana. They are abundant in Wyoming, Utah, Colorado, Arizona, New Mexico, northwestern Texas, and the western portions of Nebraska, Kansas, and Oklahoma.

In the plains areas the mounds have been built for the most part on the flats, but they also exist on valley slopes. In Wyoming and Utah they are exceptionally abundant on the flat benches above the present flood-plains. In Wind River and Big Horn basins, Wyoming, mounds are abundant upon most flat surfaces. They extend laterally to the edge of the basins, where there is a sharp change in slope and vegetation at the foot of the mountains. Vast numbers of them may be seen on the benches near Powell, Worland, Riverton, and Casper, Wyoming. They are equally abundant on the benches in such valleys as Weber and San Pete,

[1] Manuscript received May 17, 1950.

Utah. They are not restricted to flat surfaces, being common on rather steep slopes if the surface is more or less free of vegetation and the underlying rock is unconsolidated (see pl. 1). The factors of sunlight and soil conditions appear to be as important as slope.

The largest concentration of mounds that has been observed is in Wind River Basin, southwest and northeast of Shoshone, and near Powell in Big Horn Basin, Wyoming. Approximately seven mounds per acre exist in portions of Wind River Basin such as in T. 39 N., R. 92 W.; T. 1 N., R. 5 W. Counts made on many aerial photographs of Big Horn Basin show concentrations of seven mounds per acre on numerous local flats. About 10 miles east of Park City, Utah, there are also about seven per acre. Similar density has been recognized on aerial photographs from central Utah. In areas of maximum concentration about 2 per cent of the total surface is marred by mounds. Headlee and Dean (1908) reported approximately 4.6 per acre near Hays City, Kansas, in 1908, but farming has probably reduced their number since then. It is estimated that at least 3,000 square miles of Wind River Basin, Wyoming, consists of flat upland bench or terrace favorable as a habitat for the mound-building ants. A conservative estimate of three mounds per acre results in an approximate total of 6,000,000 mounds in this one basin. Observations during several airplane flights at low altitude make this figure seem reasonable.

The ants build their nests in Recent soil developed mostly on Tertiary and Cretaceous rocks. Several factors are involved in this choice of location. The flat surfaces in the Great Plains and intermontane basins are formed, for the most part, by Tertiary and Cretaceous sediments. These strata are usually composed of slightly consolidated sands and shales with a thick soil mantle. In general, the area is semiarid, and a sparse growth of vegetation can be easily cleared to permit an abundance of sunlight.

Externally, a mound is in the shape of a cone (pl. 1). The mature cones average 14 inches in height and approximately 3 feet in diameter at the base; the largest attain a height of 2 feet. Of course, the size varies with the age and size of the colony. The surface of the cone is covered with a veneer of the coarser available material, particles about $\frac{1}{4}$ inch in diameter. The angle of slope of the cone approximates 27°; slight variations from this depend on the angle of repose of the materials used in construction. These materials range through all types of igneous and sedimentary rocks, and glass, cinders, or other man-made substances may be used locally.

The mound is situated near the middle of a circular clearing. The diameter of this clearing is variable, the size depending on the age of the colony and the type of surrounding vegetation. A 12–14-foot clearing is the most common; a 20–30-foot clearing is found in some places. All vegetation in the clearing has been removed by the ants. Because all loose material on the barren surface is swept away by the wind, some of the mounds are depressed 1–3 inches below the surrounding surface.

Internally, the mound is composed of soil interstratified with thin beds of coarse ma-

PLATE 1

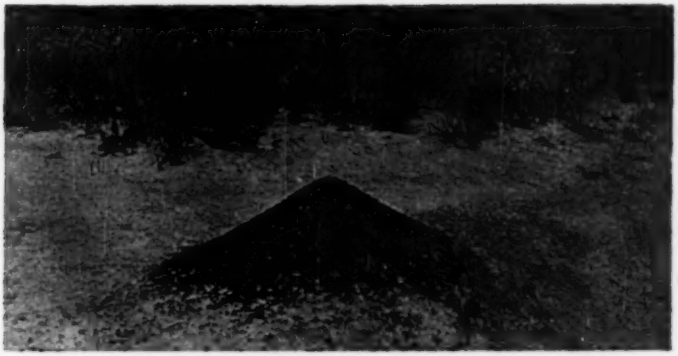
A, Mound in Rosebud County, Montana, composed of dark shale fragments.

B, Cross section of mound, 7 miles northeast of Bonneville, Fremont County, Wyoming.

C, View of mounds 7 miles northeast of Bonneville, Fremont County, Wyoming. About seventy-five mounds in view.

PLATE 2

Aerial photograph, CVT-2B-38, of area 6 miles southeast of Lyman, Uinta County, Wyoming. Anthills show as circular white dots on upland sagebrush-covered terrace. Scale, approximately 350 feet per inch. Courtesy U.S. Department of Agriculture.



A

B

C

Ant mounds in Wyoming and Montana

Aerial view of mounds

terial similar to the external veneer in size and composition (fig. 1; pl. 1, *B*). The coarse beds represent former successive surfaces during mound growth, the particles of which have been gathered from the surrounding and chambers. Activity usually extends as much as 6 feet below the surface and in places as much as 10 feet. The whole nest is a result of the excavation and construction activities of the ants. Mature cones average

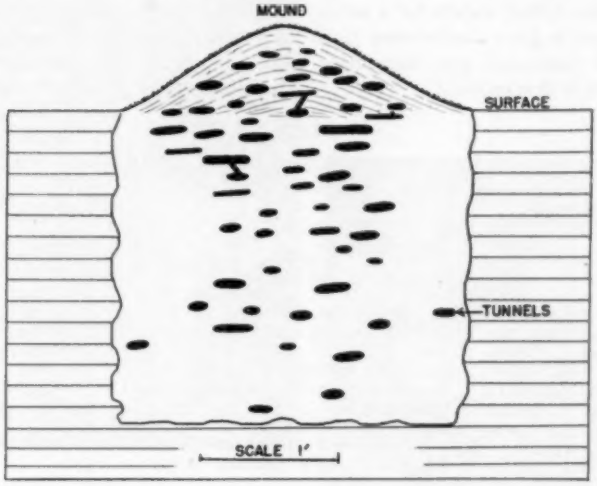


FIG. 1.—Sketch of cross section of mound and nest in subsurface

surface, whereas the soil has been brought from below during the process of tunnel construction. The mound, as well as a large area below, is honeycombed with tunnels approximately 1 cubic foot of material. As much as 50 cubic feet of soil below the surface may be modified by a complex system of rooms and galleries.

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SODACLASE-DACITE FROM THE CALIFORNIA COMPANY NO. 1 A. R. SPEARS DEEP TEST, LINCOLN COUNTY, KENTUCKY[1]

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INTRODUCTORY STATEMENT

An unusual sodaclase-dacite was encountered in The California Company No. 1 A. R. Spears deep test, Lincoln County, Kentucky, drilled June–November, 1946. This is the first "basement" rock to be reached by drill in Kentucky. Of the total drilling depth of 6,117 feet, the last 356 feet were in dacite. Fragments of dacite were found in 41 feet of complex sediment overlying the igneous body.

Formational tops, generalized lithology,

[1] Published by permission of The California Company. Manuscript received June 1, 1950.

and age determinations, as released by The California Company, are given in table 1.

SODACLASE-DACITE

The dacite is relatively uniform throughout the 356 feet drilled, except for a rather marked decrease in grain size between 5,980 and 6,020 feet. Some dark-gray slaty material also occurs in this interval.

Megascopically, the rock is a dark reddish-brown porphyry, with phenocrysts making up approximately 12 per cent of the whole. Phenocrysts are reddish-brown feldspar, commonly showing Carlsbad twinning. They have a maximum length of 12 mm. and an average of about 3 mm. The matrix is largely aphanitic, but some tiny laths of feldspar can be distinguished with the unaided eye. Irregular patches of chlorite are also visible, chiefly adjacent to phenocrysts and in small cavities. Specular and ordinary red hematite are dusted finely through the rock, and some concentrations are 0.5 mm. across.

In thin section, the matrix is seen to be holocrystalline and to consist essentially of stout laths and tablets of feldspar with minor interstitial quartz. Laths average about 0.15 mm. in length. The phenocrysts and the feldspars of the matrix are optically similar and show some properties of both albite and anorthoclase. The following determinations were made by Dr. Jewell J. Glass, of the United States Geological Survey:

Optically the indices of refraction and the optical axial angle of this feldspar correspond closely to those for normal albite; however, the twinning habit and extinction angle (extremely small, nearly 0° on 001) correspond to those for anorthoclase.

Optical properties:

Indices: $\alpha = 1.528, \beta = 1.532, \gamma = 1.537$

TABLE 1

LOG OF THE CALIFORNIA CO. NO 1 A. R. SPEARS WELL, LINCOLN COUNTY, KENTUCKY

Depth below Surface (Feet)	Thickness (Feet)	Lithology	Age*
0– 418	418	Ls., shaly ls., and limy sh.	U. Ord. (Cincinnatian)
418– 609	191	Ls.	M. Ord. (Lexington)
609–1,290	681	Ls., dense to fine crystalline	M. Ord. (High Bridge)
1,290–1,309	19	Ls., magnesian ls. and dol.	M. Ord. (Everton?)
1,309–4,310	3,001	Dol.	L. Ord. and U. Camb.
4,310–4,390	80	Ls., oölitic, somewhat magnesian	.....
4,390–5,110	720	Sh., gray, red, and green; and siltstone	.....
5,110–5,720	610	Ss., quartzitic	.....
5,720–5,761	41	Dol. and ls. with streaks of cgl., arkosic ss., and pebbles of rhyolite [and dacite]	.....
5,761–6,117	356+	Rhyolite porphyry [sodaclase-dacite]	.....

* Age determinations: Correlations below 1,309 feet (top of the Knox dolomite) are not definitely known. Fossils from cores taken in the upper part of the shale interval, 4,390–5,110 feet, were considered by Miss Christina Lochman, of Mount Holyoke College, to have Nolichucky affinities.

PLATE 1

A, Sodaclase-dacite. Laths and tablets are feldspar; minor quartz fills interstices; opaque material is chiefly hematite and leucoxene. Plane-polarized light. ×100.

B, Sodaclase-dacite. Phenocrysts and crystal tablets of the matrix are dominantly albite. Large phenocryst shows twinning like that of anorthoclase. Dark irregular border on large phenocryst and thin dark replacements in small phenocryst are orthoclase. Crossed nicols. ×22.

C, Sediment overlying the dacite. Dacite, *D;* quartz-feldspar intergrowths from rhyolite, *Ri;* quartz, *Q;* perthite, *P;* limestone, *Ls*. Finer grains or matrix are chiefly quartz and microcline. Dark cement is carbonate. Crossed nicols. ×22.

Sodachae-dacite and overlying sediment

Positive (+) $2V = 60°$
Dispersion distinct
Twinning is the combination of the albite and microcline lamellar types with extremely narrow albite bands.

All feldspars show slight alteration to kaolinite and are colored reddish by hematite. Some phenocrysts and, more rarely, feldspars of the matrix show borders of orthoclase (pl. 1, *B*). These appear to be overgrowths in part and replacements in other parts. Replacement orthoclase is also found along fractures in some phenocrysts. Quartz occurs sparingly in the matrix as an interstitial filling and also in coarser masses with chlorite and normal albite in rounded cavities. Some chlorite occurs in minute veinlets and irregular masses and as a probable alteration product from some ferromagnesian mineral. Hematite and leucoxene are finely disseminated throughout the rock. Apatite is a common accessory. Approximate average percentages are given in table 2.

TABLE 2

AVERAGE MINERALOGIC COMPOSITION OF THE SODACLASE-DACITE

Mineral	Percentage
Essential minerals:	
Albite	
In phenocrysts	12
In matrix	68
Quartz	8
Hematite	4
Accessory minerals:	
Orthoclase	1
Apatite	1
Zircon	Rare
Fluorite	Rare, in cavities
Secondary minerals:	
Hematite	1
Leucoxene	1
Chlorite	2
Carbonate	2

SEDIMENT ABOVE THE DACITE

Drill cuttings show 41 feet of heterogeneous sediment containing fragments of dacite overlying the dacite body. Included within this 41 feet are red and green shale, finely crystalline white limestone, light-gray dolomite, and coarse sand and conglomeratic layers. A core taken at 5,722–5,732 feet consisted of mottled dark reddish-brown and pale olive conglomeratic sandstone. Study of thin sections showed this part of the sediment to be polymodal with regard to grain sizes (pl. 1, *C*). In the analysis in table 3, the larger sizes are classed as grains and the smaller as matrix.

TABLE 3

ANALYSIS OF CONGLOMERATIC SANDSTONE ABOVE DACITE

Material	Approx. Percentage	Grain Size (Mm.)	Rounding
Grains:			
Rock fragments	24	Max. 10; av. 2	SA–SR
Quartz	32	Max. 10; av. 0.5	R
Perthite	4	Max. 1; av. 0.4	R
Matrix:			
Quartz, Microcline, Orthoclase, Rock fragments	5	Av. 0.075	A–SR
Cement:			
Dolomite, Calcite	35	Finely crystalline	

Rock fragments are chiefly subrounded sodaclase-dacite and rhyolite, consisting of intergrowths of quartz and turbid feldspar having the indices of refraction of potash feldspar. Most fragments of dacite closely resemble the underlying igneous rock, although some are considerably finer grained and show flow structure. Some contain apparently devitrified glass. Intergrowths from rhyolite generally show a ratio of quartz to feldspar of about 7 to 3, and sizable areas of quartz extinguish as units. Rounded fragments of quartz-microcline granite, vein quartz, siliceous siltstone, quartzose sandstone, a quartz-garnet rock, and dolomite also occur.

Mineral grains are mainly quartz, but microcline, orthoclase, perthite, and plagio-

clase are found. The quartz is frosted and shows unusual rounding and sphericity. Some contains fine needles of rutile and planes of liquid inclusions. Feldspar grains are also very well rounded. Albite with uncomplicated twinning occurs sparingly. One mass of spherulitic quartz or chalcedony and a few rounded garnets were noted.

The matrix consists chiefly of subangular quartz, but microcline is common, and zircon and tourmaline occur sparingly.

Loose packing of grains and fragments is characteristic. The relatively large interstices are filled with finely crystalline dolomitic cement.

OCCURRENCE AND ORIGIN

Data are insufficient to show definitely whether the dacite body is intrusive or extrusive. An intrusive origin is suggested by the rather uniform texture and mineral content, the abundance and size of the phenocrysts, the almost phaneritic character of the matrix, the lack of flow structure, and the finer grain and slaty inclusions in the interval 5,980–6,020 feet.

The finer-grained dacite and devitrified glass fragments in the overlying sediment could well have been derived from an extrusive, but their derivation from the main body of dacite drilled is not certain.

The occurrence of subrounded and partly kaolinized fragments of dacite in 41 feet of overlying sediment indicates that the igneous body had considerable lateral extent and that it is older than the sediments above. The age of the dacite may be Lower Cambrian or late pre-Cambrian.

The diverse nature of included material in the sediment overlying the dacite indicates a complex origin. It was possibly deposited near shore, where waves and currents mixed worked-over beach or dune sands, materials being eroded locally, and materials being supplied by streams. Lack of close packing in the sediment suggests that the carbonate was being precipitated as the detrital material settled out.

ACKNOWLEDGMENT.—The writer is grateful to The California Company for use of drill cuttings, cores, thin sections, and permission to publish this paper.

VERTEBRATES FROM THE CHOZA FORMATION, PERMIAN OF TEXAS[1]

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Work on the post–Arroyo Clear Fork beds of north-central Texas, reported in 1948 (Olson), has now been extended to the highest formation of the Clear Fork group, the Choza. The present note is a preliminary report on vertebrates found in beds of this age in Knox and Foard counties, Texas.

The top of the Vale formation in the type area is marked by the Bullwagon dolomite. This marker does not extend into the redbeds area, so that accurate subdivision of the rocks into Vale and Choza equivalents is difficult. There exists in this area, however, a zone of rapid change from the irregularly bedded, channeled clays and sandstones, believed to be late Vale in age, to more evenly bedded clays and sandstones, in which the frequency of channels is greatly reduced and the percentage of evaporites notably increased. The position of this transition zone, which is 50–75 feet thick, is shown on the map (fig. 1) by the line separating the Vale and the Choza. The zone is thought to be correlative in time with the changes that occurred in the marine type section immediately following the deposition of the Bullwagon. No precise boundary can be determined, but it seems highly probable that the beds above the transition zone are Choza in age. From this zone to the disconformable contact with the overlying San Angelo sandstone, the red beds show an increase in evenness of bedding and percentages of evaporites, accompanied by re-

[1] Manuscript received December 29, 1950.

duction of the relative number of channels. This section, based on a regional dip of about 50 feet per mile, is between 700 and 800 feet in thickness.

Vertebrates are now known in the lower two-thirds of the section. They occur either scattered or in concentrations of green nodules in red clays, as scraps in sheet conglomerates, and in fine to coarse channel deposits. Two types of occurrence warrant special notice. In various places, as at site 3 on the map, there occur thinly bedded, light-colored clays with limited areal extent. The beds at the margins of these deposits

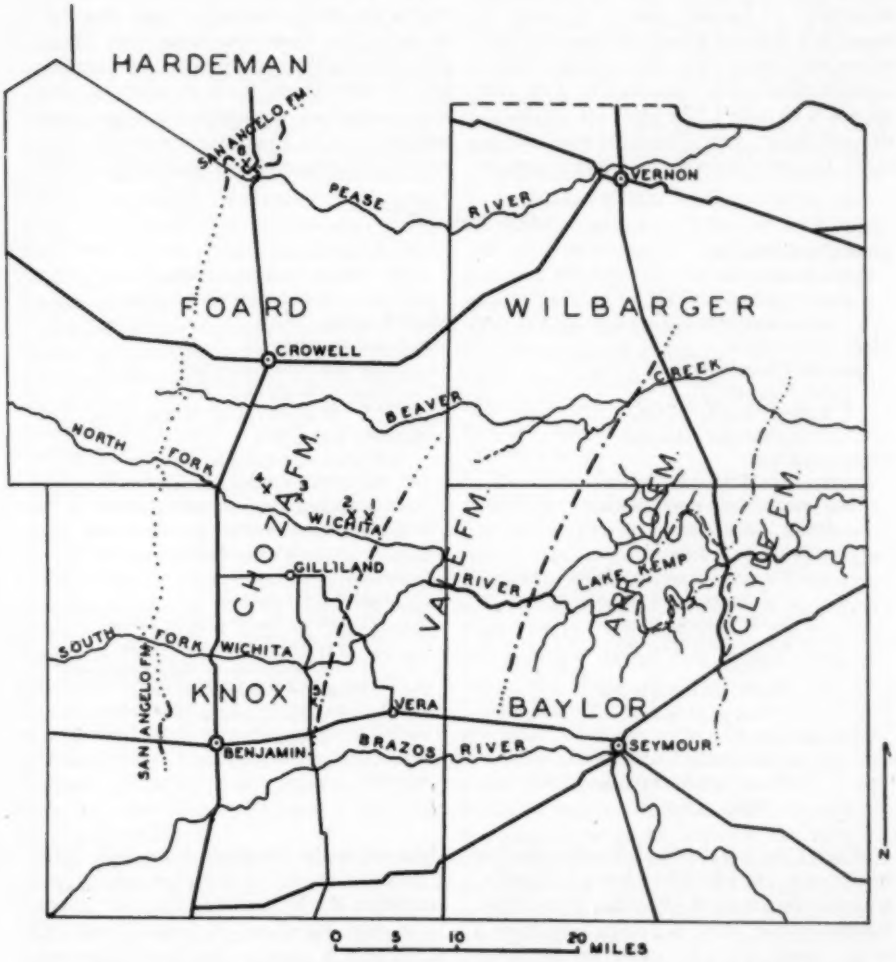

FIG. 1.—Sketch map, showing Choza localities and provisional formational boundaries, drawn approximately along sedimentary transition zones. Sites: *1*, pipe locality; *2*, "*Diplocaulus*" locality; *3*, plant locality, playa lake deposits; *4*, locality yielding latest known Choza vertebrates; *5*, southernmost known producing Choza locality; *6*, San Angelo vertebrate locality.

dip sharply toward the center of the more or less oval areas of outcrop. The clays appear to have been deposited in playa lakes. Leading to them, commonly at several levels, are fine- to medium-grained conglomeratic channel deposits. Vertebrate remains generally occur in these channel deposits, whereas the lake beds contain only poorly preserved plant remains. A second occurrence of interest (site 1 on map) is found in a series of hills in the lower Choza, where red clays are set with vertical "pipes" that are elliptical in cross section, with long axes of 6–12 inches. The pipes are of composition different from that of the surrounding clays. It seems probable that they represent tree stumps that were partly covered by the clay, rotted out, and then filled. These pipes as well as the surrounding clays contain well-preserved remains of vertebrates.

Most specimens from the Choza are fragmentary. Many are badly damaged by gypsum-bearing waters, and some are merely casts. The faunal list given below is based largely on fragmentary materials and includes the genera that have been identified to date plus those specimens that can be placed in higher categories without certain generic identification. It is probable that other genera are represented in unprepared materials or in fragments for which taxonomic assignment has not as yet been made.

FAUNAL LIST

Class Chondrichthyes
  Order Xenacanthodii
    Family Xenacanthidae
      Xenacanthus sp.
Class Osteichthyes
  Subclass Choanichtyes
    Order Dipnois
      Family Gnathorhizidae
        Gnathorhiza dikeloda
Class Amphibia
  Subclass Apsidospondyli
    Superorder Labyrinthodintia
      Order Rhachitomi
        Suborder Edopsoidea
          Family Trimerorhachidae
            Trimerorhachis cf. *insignis*
        Suborder Eryopdoidea
          Family Eryopdidae
            Eryops?
          Family Dissorophidae
            Cacops cf. *broilii*
  Subclass Lepospondyli
    Order Nectridia
      Family Diplocaulidae
        Diplocaulus sp.
      Order Microsauria
        Family Lysorophidae
          Lysorophus cf. *tricarinatus*
Class Reptilia
  Subclass Parareptilia
    Order Seymouriamorpha?
      Family Waggoneriidae
        Waggoneria cf. *knoxensis*
  Subclass Eureptilia
    Infraclass Captorhina
      Order Captorhinomorpha
        Family Captorhinidae
          Captorhinus?
          Labidosaurikos?
    Infraclass Synapsida
      Order Pelycosauria
        Suborder Sphenacodontoidea
          Family Sphenacodontidae
            Dimetrodon cf. *gigashomogenes*
        Suborder Edaphosauroidea
          Family Caseidae
            Casea?

Among the fish, teeth of *Xenacanthus* are moderately abundant in channel deposits, whereas *Gnathorhiza dikeloda*, a common lungfish of the Vale, is known only from a single lower jaw and tooth in the lower Choza. *Lysorophus* is by far the most abundant amphibian. It occurs in concentrations in red clays at several sites but has not been observed in the channels. *Trimerorhachis* is a common animal at the pipe locality, occurring in the pipes and in the clay proper. It is rare elsewhere. A large *Eryops*-like amphibian is known from skull fragments found at two sites in the middle Choza. One of the specimens shows the orbits to have been more anterior in the skull than in

Eryops megacephalus, leaving the generic assignment uncertain. *Cacops* is known from humeri recovered from the pipe locality. *Diplocaulus* occurs in some concentration in fine-grained channel deposits at a single locality (site 2 on map) in the lower Choza and has been found in sheet conglomerates as high as middle Choza. As in the Vale, this genus is unknown from the clays.

Among the reptiles, the captorhinomorphs are represented by fragmentary specimens. Generic assignments will remain uncertain until it has been possible to study more complete materials. Specimens tentatively assigned to *Captorhinus* include jaws, parts of skulls, vertebrae, and limb bones. All are considerably larger than comparable parts of *Captorhinus aguti* from the Arroyo and Vale but are otherwise similar. Comparable specimens are found in the Vale. Larger specimens, with a tooth pattern like that of *Labidosaurikos*, have been found, and assignment to this genus is the most reasonable one that can be made at the present. These determinations may be considerably modified, once more material has been studied in detail.

The only large predator among the reptiles is *Dimetrodon*. No definite differences from *Dimetrodon gigashomogenes*, which is known in the Arroyo and Vale, have been noted in the skull fragments, vertebrae, and limb bones that have been found. A large pelvis, two femora, a tibia, and associated caudal and posterior presacral vertebrae, found in evenly bedded red clay, pertain to a large caseid. The pelvis corresponds in size and general structure to that of *Cotylorhynchus romeri*, but the femora, associated with the pelvis, are much shorter. Proportions are more those of *Casea* of the late Arroyo and Vale.

The Choza vertebrate fauna is a direct continuation of that found in the underlying Vale. Few generic differences have been observed, and some species are identical. Rather marked faunal changes occurred at about the time of the introduction of Vale deposits in the area under consideration, changes about comparable in scope to those marking the transition from Wichita to Clear Fork times. *Cacops* and *Casea* appeared for the first time in late Arroyo or early Vale time, as did the large species of lungfish, *Gnathorhiza dikeloda*. These persisted into the Choza. The captorhinomorphs began a rapid deployment into a series of types as large as, and larger than, *Labidosaurus*, and most forms are characterized by multiple rows of teeth. This radiation is known to have continued at least until San Angelo times. Certain reptilian genera characteristic of the Arroyo have not been found in the Vale or Choza. Notable among these are *Edaphosaurus* and *Diadectes*, both large and easy to recognize. The changes introduced at the beginning of the Vale resulted in a fauna that persisted with little change until at least the middle Choza. Differences in percentages of genera in the collections from the Vale and Choza probably have little significance in view of the smallness of samples and the differing conditions of deposition.

The abundance of fossil remains decreases steadily in successively younger beds in the Choza, and this may well be due to increasingly unfavorable conditions for vertebrate life as conditions conducive to the formation of evaporite basins came into existence. Beds of late Choza age show little promise of yielding a fauna. San Angelo deposits were laid down disconformably on the Choza after what may have been an appreciable lapse of time. They are more favorable for vertebrates and have yielded a few specimens. The scant evidence now available suggests a rather radical change in the vertebrate fauna between the middle Choza and San Angelo. Prospects of obtaining a post–San Angelo fauna in King, Cottle, or Hardeman County are poor, for the beds are predominantly marine and marked by thick beds of dolomite and anhydrite.

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REVIEWS

Geologia applicata all'ingegneria. By ARDITO DESIO. Milan: Ulrico Hoepli, 1949. Pp. xxvii+851; figs. 305.

Professor Desio, of the Geologic Institute of the University of Milan, Italy, is a geologist of widely diverse interests and prolific productivity. His massive textbook on "Geology Applied to Engineering" is based on an extensive background of professional accomplishment. Some idea of the range of coverage of the volume may be gained from the headings of the five main sections: "Underground Exploration," "Applied Hydrogeology," "Applied Geomorphology," "Construction Geology," and "Mineral (or Economic) Geology." The fundamental principles of geology are presented as the basis for their application to practical problems.

Structural and historical geology are outlined in the section on "Underground Exploration" as the logical basis for the explanation of geologic maps and mapping, geophysical exploration, and exploratory well drilling. The section on "Applied Hydrogeology" treats of surface and subterranean waters and provides interesting detail in the treatment of springs, especially thermal and mineral springs, so prominent in Italian geologic literature. Geologic processes are explained in the section on "Applied Geomorphology." The "Construction Geology" section discusses building stone, construction materials, foundations, roads, canals, railways, mines, dams, airports, and cemeteries —as complete and thorough a coverage as could be expected in a single-volume textbook of this nature. The section on "Economic Geology" discusses magmatic and sedimentary ore deposits, coals, and hydrocarbons with a final chapter on prospecting and advice to prospectors.

The principles explained in the text are abundantly demonstrated by examples from all parts of the world, but especially, of course, from Italy. The illustrations, particularly the line drawings, are profuse and well done. Photographs are abundant and significant but are unfortunately not of so good quality in their reproduction as is customary in textbooks of this country. The book will be found well worth while by those interested in geology as applied to engineering problems, particularly those problems significant in the development of Italy today, and their treatment.

ELEANOR TATGE

National Bureau of Standards

Les Éruptions 1938–1940 du Volcan Nyamuragira. By JEAN VERHOOGEN. ("Exploration du Parc National Albert, Missions J. Verhoogen 1938 et 1940," Fasc. 1.) Brussels: Institut des Parcs Nationaux du Congo Belge, 1948. Pp. 186; figs. 12; pls. 27; tables 14.

The East African volcano Nyamuragira was in continuous eruption from January, 1938, to June, 1940. For a period of seven months at the beginning of the eruption and another period of three months near its end, Dr. Verhoogen was stationed as an observer at the volcano. From his own careful observations and from reports given him by others, he has put together this detailed account of the volcano's activity. His work was abruptly terminated by the invasion of Belgium in May, 1940, but by that time he had completed a series of measurements of lava temperatures, of magnetic anomalies, and of gas compositions which, combined with day-to-day observations, provided him with a basis for some novel theoretical ideas about the mechanism of eruption.

The text is divided into two parts: the first two-thirds consists of a description of the volcano and a detailed record of its activity during the eruption, while the final third contains the results of spectroscopic, magnetic, and pyrometric measurements, a chemical and petrographic description of the products of eruption, and a discussion of the eruptive mechanism. Twenty-seven excellent plates complete the volume. Unfortunately, maps are limited to two small sketches, which fail to locate several of the frequently mentioned geographic details.

Nyamuragira is one of a group of volcanoes in the part of the Rift Valley of East Africa between Lake Kivu and Lake Edward. It is a typi-

cal shield volcano, with a complex caldera at its top. For at least ten years preceding the 1938 eruption the caldera had shown Hawaiian-type activity, lava pools forming and gradually filling the lower part of the caldera, until in January, 1938, the lava reached nearly to the low point of the caldera rim. The eruption proper commenced late in the month, with sinking of part of the caldera, extensive fissuring of the volcano's flanks, and emission of lava from some of the fissures. Within a few days the entire activity was concentrated in one area of fissuring far down on the southwestern slope, where a new lava pool formed, two small cones were built up, and a flow started moving down onto the plain near Lake Kivu. The activity in this area, which Verhoogen calls by the local name of "Tshambene," constitutes the 1938–1940 eruption. Verhoogen likens the relationship of Tshambene and Nyamuragira to that between Kilauea and Mauna Loa.

The history of the eruption is a record of changes in the form and activity of the lava lake, the dying of old spatter cones and the birth of new ones, and a continuous, though nonuniform, flow of lava. Activity gradually slackened during the first six months, remained fairly constant for a year and a half, and then in 1940 again diminished and ceased altogether in June of that year.

Some of the older ideas about lava lakes cannot possibly apply to Tshambene, according to Verhoogen's observations. The lake cannot be pictured, for example, as the top of a long column of molten lava, with circulation maintained by convection; for it evidently originated by lateral draining of lava from under the volcano, its visible circulation consisted of horizontal flow from under one bank to the other, its temperature was approximately constant at all points of the surface and over a long period of time, and at least part of it was demonstrably shallow when the lava receded. Nor could Verhoogen find any evidence that gas played a significant role in the circulation of the lake, except that lava fountains formed in places where cooled blocks with entrapped air were engulfed by the liquid. Verhoogen regards the lake as an accidental external manifestation of lava movement within the volcano, its circulation being maintained and altered by internal conditions not directly observable.

Gas in general appeared to play a much less important role in the eruptive activity than is usually assigned to it. Rough figures for the amounts of gas emitted by the cones were obtained by estimating the size of the orifices and the rate of gas escape; comparison of these figures with the rate of flow of lava showed that the lava contained considerably less than 1 per cent of gas by weight and hence was undersaturated. The separation of gas from lava, despite the apparent lack of supersaturation, Verhoogen explains by the escape of gas at depth from lava under pressure, the gas itself being under less pressure because of its ability to move through small openings.

Lava temperatures were remarkably constant, averaging about 1,070° C. The measurements gave no indication that gas reactions, combustion of gases, or escape of gases had more than small and local effects on magma temperatures.

Spectroscopic study of flames from the cones was carried out with a small glass-prism instrument, the only one immediately available. Sodium, potassium, and nitrogen were the only elements identified in the spectrograms. The N_2 bands, surprisingly, indicated a state of excitation far higher than that corresponding to the observed temperatures. Verhoogen concludes that the nitrogen was probably juvenile, having acquired its excess energy at depth.

Magnetic measurements were made with a simple dip needle. The amount of dip at any one place apparently depended largely on the temperature of the lava below the surface, the temperature determining whether the contained magnetite was above or below its curie point. Verhoogen suggests that the dip needle may prove generally useful in detecting the presence of fluid lava beneath the surface.

The lavas of the 1938–1940 eruption are dominantly thin flows of alkali-rich mafic types, with pahoehoe surfaces, similar to earlier flows from Nyamuragira and adjacent volcanoes; but they differ in that their ratio of Na/K is equal to or greater than 1, whereas it is less than 1 for most of the other flows. The sublimates are interesting, in that the dominant anion is sulfate; because of the extreme nonvolatility of the alkali-metal and alkaline-earth sulfates, Verhoogen suggests that the salts may be carried chiefly as solid particles suspended in gas.

In contrast to the usual hypothesis that mafic lavas originate deep within the crust, Verhoogen suggests that magma may be generated by metasomasis and fusion at high levels, in part within the volcanic structure itself. Although he discounts the role played by

gases in the external phenomena of the eruption, he regards gases from great depths, bringing with them much thermal and chemical energy as the probable agents of large-scale fusion.

It is impossible within the limits of a review to discuss adequately the wealth of evidence that Verhoogen brings to the support of his hypotheses. Nor is there space for more than a mention of the many interesting details about lava movement, about phenomena accompanying the entrance of the lava flow into Lake Kivu, and about terraced structures of the volcano. Altogether, the book is at once a careful factual record of many aspects of an important volcanic eruption and a stimulating discussion of possible theoretical interpretations.

KONRAD B. KRAUSKOPF
Stanford University

Selenium: Its Geological Occurrence and Its Biological Effects in Relation to Botany, Chemistry, Agriculture, Nutrition, and Medicine. By SAM F. TRELEASE and ORVILLE A. BEATH. New York: The Authors, 1949. Pp. x+292; figs. 61; tables 43. $5.50.

This book is another useful addition to the group of short monographs on the elements. The authors, representing botany and chemistry, are experts in much of the field covered in their book and consequently have produced an authoritative and comprehensive survey. This book, the first one to be published on selenium, contains much unpublished material from the authors' notebooks.

The book starts with a historical review of poisoning in livestock caused by ingestion of seleniferous plants (chap. i). Chapter ii treats in detail the selenium indicator plants. Much valuable taxonomic information is given in this chapter, including a key to indicator species of the important genus *Astragalus*. Chapter iii, in which the distribution of selenium in rocks and soils is discussed, should be of much value to the geologist and geochemist interested in that element. A detailed account is given, in this chapter, of selenium-bearing formations of various geologic ages and on the distribution of seleniferous vegetation in western United States. The accumulation of selenium by plants is exhaustively treated in chapter iv. This chapter should prove stimulating reading for those interested in geobotanical and biogeochemical prospecting. The following chapters (v, vi, and vii) treat selenium poisoning in animals, selenium in relation to public health, and prevention and control of selenium poisoning respectively. The chemistry of selenium is outlined in the last, the eighth, chapter of the book. The discussion of analytical methods in this chapter includes also the determination of selenium in rocks. The volume contains, further, a valuable Bibliography of almost three hundred titles and, in addition, author and subject indexes. The text is illustrated by numerous excellent photographs, diagrams, and maps.

The authors have left little opportunity for the reviewer to find any defects in their work. However, one of the classic contributions to the geochemistry of selenium, by V. M. Goldschmidt and O. Hefter, has passed unnoticed by the authors. They evidently subscribe to the hypothesis that all selenium present in sedimentary rocks is of volcanic origin. But, even though there is adequate material at hand showing the content of selenium in sediments and sedimentary rocks, its abundance value in igneous rocks is only tentative, and virtually nothing is known of its content in the various classes of igneous rocks. With reference to the discussion of the manner of occurrence of selenium in igneous rocks (p. 106), one should notice that, owing to the similarity of the ionic radii of binegative selenium and sulfur, selenium evidently replaces sulfur diadochically in sulfide minerals of igneous rocks. The reviewer also thinks that it would be worth while to consider sorption compounds as a plausible reason for the occurrence of selenium in soil; the authors seem to explain all selenium in soil as water-soluble selenates, selenites, and organic selenium compounds; free selenium; selenides; and basic ferric selenites (p. 110).

But these are remarks of minor importance, and the fact remains that the authors have written a lucid, readable, and recommendable account of their element.

KALERVO RANKAMA
University of Chicago

Geology and Mineral Deposits of an Area North of San Francisco Bay, California. By CHARLES E. WEAVER. (*California Department of Natural Resources, Division of Mines Bull.*, no. 149.) 1949. Pp. 135; figs. 4; pls. 24. $4.00.

This bulletin is a condensation of the paper, *Geology of the Vacaville, Antioch, Mount Vaca, Carquinez, Mare Island, Sonoma, Santa Rosa, Petaluma, and Point Reyes Quadrangles, California*, which appeared as Memoir no. 35 (1949) of the Geological Society of America. In addition to the descriptive material on geology and mineral deposits, there is a series of sixteen colored geologic and economic maps printed on standard U.S. Geological Survey topographic quadrangles.

LOU WILLIAMS PAGE
University of Chicago

Geology of India and Burma. By M. S. KRISNAN. Madras: Law Journal Office, 1949. Pp. 544; figs. 14; pls. 22; tables 50; geol. map. Rs. 19.

This work by Dr. Krisnan, of the Geological Survey of India, is an excellent compendium that compresses an enormous amount of information gathered over a period of more than one hundred years into a volume of convenient size. It is largely descriptive, but discussions of structural developments, paleogeographic interpretations, and mineral resources are included at irregular intervals. The organization, which follows in general that of Wadia's *Geology of India*, is good, and the space devoted to the rocks of different ages and areas seems to be an accurate reflection of their relative importance and the extent to which they are known, without undue emphasis on any part. The text includes numerous generalized stratigraphic and correlation tables and a few lists of fossils and is illustrated by geologic maps and sections and several plates of fossils. Most chapters are accompanied by selected bibliographies. The map, at a scale of 96 miles to 1 inch, shows the geology by sixteen colored patterns.

The geology of India, one of the largest countries in the world, is unusually complex. Two regions, separated by the Indo-Gangetic alluvial plain, are sharply differentiated and have almost no features in common. The peninsula is composed largely of unfossiliferous rocks, mostly pre-Cambrian in age. The thick sedimentary sequence of the Himalayan belt, many of whose formations contain abundant fossils, has been greatly disturbed by orogenic diastrophism. Adequate geologic investigation has not been easy in either region.

The oldest rocks of the peninsula are of Archean type and consist of gneisses, with which are associated more or less extensive bodies of schist, the latter being collectively known as the "Dnarwar system." These rocks occupy about two-thirds of peninsular India and also the island of Ceylon. They are succeeded, above a widespread unconformity, by Algonkian-like metamorphosed pre-Cambrian sediments of the Cuddapah system. Later sediments are divided into the Vindhgan and Gondwana systems. The former are believed to be of Cambrian and possibly late pre-Cambrian age, but the occurrence of bright coal lenses in the part lower strongly suggests that, locally at least, these beds are much younger. They contain few, if any, recognizable fossils. The latter are supposed to range from Upper Carboniferous to Lower Cretaceous and include all the important coal deposits of India. Both probably were deposited mainly under nonmarine conditions. Later sediments from Cretaceous to Recent are sparingly represented in narrow coastal zones only. The Deccan trap, probably of Paleocene age, blankets most of the northwestern third of the peninsula.

Pre-Cambrian rocks occur throughout the length of the Himalayas, but they have been inadequately studied and at present cannot be subdivided similarly to those of the peninsula. Fossiliferous early and middle Paleozoic formations are probably represented fairly completely, but they are little known except at a few localities. Perhaps they have been altered generally almost beyond recognition. The Tethys Sea came into existence in Permian time, and in it marine sediments accumulated until the end of the Eocene. This episode was concluded by great uplifts in the Himalayan area, and later Tertiary and more recent sediments are mainly of continental types. Mountain-forming movements have continued up to very recent time, and strata of presumed Pleistocene age are locally much disturbed.

This work is much more comprehensive and detailed and describes a more extensive area than did Wadia's book with a similar title. It is a reference work and not a text, and consequently several brief general sections that seem to be aimed at the beginning geology student are out of place and could better have been omitted. Its greatest deficiency is a lack of documentation that is not compensated by the individual chapter bibliographies. Also, the reader will find it necessary to refer constantly to a good geographic atlas to locate the many places mentioned in the text which are not shown on the geologic map. As is almost in-

evitable in a compilation of this kind, some inconsistencies have not been eliminated, and the author could have profited from the advice of a competent modern paleontologist in connection with some of his interpretations of environments and other paleogeographic matters.

On the whole, this book is a very valuable and welcome addition to the literature on regional geology. The part that is likely to be of most interest to foreign geologists is the chapter devoted to the Gondwana system, which reviews the stratigraphy, structure, and floras of the strata that have contributed so importantly to the recognition of late Paleozoic glaciation and the formulation of the hypothesis of continental drift which Krisnan appears to accept without reservation.

J. MARVIN WELLER

University of Chicago

Lehrbuch der Paläozoologie. By O. KUHN. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung, 1949. Pp. 326; figs. 224; tables 50. DM. 30.

This book presents a systematic outline of fossil animals. About two-thirds is devoted to the invertebrates and one-third to the vertebrates, and approximately one-fourth of the space is occupied by illustrations. In such a comparatively small book, however, it has been impossible to consider adequately either the classification or the morphology of the whole animal kingdom. Also, different groups are quite unequally treated, and the author seems to have shown preference for post-Paleozoic forms and certain groups with which he is most familiar. As an indication of the amount of coverage, the following estimates of the text (exclusive of illustrative material) devoted to certain groups may be compared: sponges, 6 pages; corals, 11 pages; crinoids, 6 pages; cystoids, $1\frac{1}{4}$ pages; bryozoans, 2 pages; brachiopods, 8 pages; pelecypods, 10 pages; trilobites, 3 pages; ostracodes, $\frac{1}{3}$ page.

This publication cannot be considered a "Manual of Paleozoölogy." It is too brief to be a manual, and it is overwhelmingly systematic rather than zoölogic in the sense that fossils are considered as once living animals. Classification in most groups is not carried below orders, under which a few genera may be briefly characterized as examples. The classification presented contributes practically nothing. Most of it appears to have been adapted from a few standard works available in most libraries, and parts of it are greatly out of date. For example, the crinoid and ammonoid orders recognized are now employed by few, if any, specialists. Also, no zoölogic classification at all is indicated within such groups as the Foraminifera and trilobites. The figures, copied from previous publications, are mostly good, and these are probably the best part of the book. However, they are not always chosen to illustrate the groups under consideration to best advantage. Bibliographic references are very few.

J. MARVIN WELLER

University of Chicago

Structure of Typical American Oil Fields: A Symposium on the Relations of Oil Accumulation to Structure, vol. 3. Edited by J. V. HOWELL. Tulsa: American Association of Petroleum Geologists, 1948. Pp. 516.

This addition to a well-known series consists of twenty-four papers describing oil fields in twelve states and Canada. The fields described include both new and old ones and exemplify most of the common types of oil traps as well as several that are more or less unique. The papers likely to be of most interest to nonprofessional oil geologists describe the following fields: Also Canyon, California, and Rose Hill, Virginia (structures below overthrusts); Apco, Texas (buried hogback hill); Creole, Louisiana (faulting in Gulf of Mexico, includes account of directional drilling); Cymria, California (structure beneath an unconformity); Edison, California (production from metamorphic rock); Kraft-Prusa, Kansas (structure below unconformity and sands above it, structure over pre-Cambrian hills); Marine, Illinois (Silurian reef); Omaha, Illinois (dome cut by igneous intrusions); and West Edmond, Oklahoma (stratigraphic wedge-out on monocline below unconformity). The text is profusely illustrated by maps and sections and by thirteen larger folded plates.

J. MARVIN WELLER

University of Chicago

Einführung in die Mineralogie (Kristallographie und Petrologie). By C. W. CORRENS. Berlin, Göttingen, Heidelberg: Springer-Verlag, 1949. Pp. viii+414; figs. 405; 1 table. DM. 38; bound, DM. 41.60.

This book is an interesting introduction to mineralogy and its relationship to petrology and crystal chemistry. It symbolizes the present-day rapid change in some branches of geology from the descriptive cataloguing stage to the interpretative analyzing and constructive stage. The author has used little space for description of minerals; instead, he has put this material in short tabular form in an appendix. The main portion of the book is devoted to modern chemical physics of the crystalline state and to petrology. There are three major sections: (1) "Kristallographie," with emphasis on crystal chemistry; (2) "Petrologie," in which genetic aspects are stressed; and (3) "Anhang," in which the pertinent properties of minerals and crystals are presented in handy tables. There is no chapter headed "Mineralogie" in this textbook of mineralogy. Mineralogy in modern geology has significance only as an integral part of petrology and of crystal chemistry in its widest sense. This is clearly demonstrated in Correns' book.

The section on crystallography does not devote too many pages to description of external properties of crystals, although the laws of crystallography *sensu stricto* are sufficiently discussed to give the students enough information. The chapter is mainly concerned with the fundamental physicochemical characteristics of the crystalline state. The author considers in some detail the concept of lattice energy and the several types of bonds which keep the constituents of crystals together. Pertinent drawings of crystal structures and electron density maps help to make the presentation clear and interesting. The theory of disorder and dislocation in the crystalline state is discussed. Crystal growth and dissolution are treated in consistence with the theory of lattice energy. Plasticity, strength, and elasticity of crystalline substances are discussed on the basis of crystal structure and interionic energies.

Sufficient space has been devoted to optical crystallography and to X-ray theory and methods. This first section on crystallography amounts to 150 pages and is, in the reviewer's opinion, the best part of the book.

The second section on petrology starts with the physicochemical foundation of rock genesis. The kinetics of crystal formation and the laws of chemical equilibrium in systems pertinent to rock formation are considered. The discussion of equilibrium is rather weak, although one would have to turn to texts in chemical physics to find anything better. Correns apparently considers the phase rule of Gibbs as the controlling factor of equilibrium. The very important concepts of free energy and entropy and their dominant role in the theory of equilibrium should be emphasized strongly in such a book, which actually deals with the physicochemical fundamentals of rock-making processes. A reproduction of the equilibrium diagram leucite-silica (p. 164) is erroneous: the eutecticum is displaced by 10 per cent. Correns may perhaps have taken this figure directly from the book by Barth, Correns, and Eskola, *Die Entstehung der Gesteine*, instead of going back to the original source.

The magmatic, sedimentary, and metamorphic-metasomatic rocks are all treated from a genetic viewpoint. The chapter on sedimentary rocks is the best, as one would expect, since it represents the main field of interest of the author. The section on petrology is closed by a chapter on geochemistry.

The third and last section of the book, in tabular form, is concerned with crystallography and mineralogy.

The book contains much interesting historical information. In the reviewer's opinion, it is a good introduction to modern "mineralogy" for beginning students. It is also worth-while reading, for example, for specialists in X-ray crystallography who would like to have a brief but comprehensive view of the significance of their science for petrology and for petrologists who may need an introduction to modern crystal chemistry. It has little information, however, for mineralogists hunting for exhaustive descriptions of mineral species and their localities.

Paper and binding are unfortunately not good.

HANS RAMBERG

University of Chicago

Time and Its Mysteries, Series III. Four lectures given to the James Arthur Foundation, New York University, by HENRY NORRIS RUSSELL, ADOLPH KNOPF, JAMES T. SHOTWELL, and GEORGE P. LUCKEY. New York: New York University Press, 1949. Pp. x+126. $3.00.

After nine lectures on time—by three physicists, two anthropologists, two astronomers, a historian, and a philosopher—the

James Arthur Foundation has finally heard from a geologist, Adolph Knopf of Yale, on "Geologic Records of Time," a lecture included in this third volume. Professor Knopf's historical summary, written in 1941, is a lucid account of the development of radioactive methods for determining the ages of the oldest rocks and gives geology due credit (which I have not seen in other semipopular accounts) for providing the basis and confirming the assumptions of physics in this matter.

Each lecture is about thirty pages in length and is written in semipopular style by an authority who, because of the basic nature of the time concept, covers those fundamental parts of his field of interest to all scientists. For instance, the first lecture in this volume, by Henry Norris Russell, of Princeton, describes three independent astronomical estimates of the age of the universe, in addition to the geophysical estimate of the age of the earth, all of which have the same order of magnitude: about three billion years. Even though Russell's lecture was given over ten years ago, he draws attention, with his customary shrewdness, to discrepancies in our concept of a unique age of the universe—discrepancies which are the basis for research today. As an example, he notes that the giant and supergiant stars are radiating energy so rapidly that they can last no longer than one-hundredth of the estimated age of the universe, a fact recently used by Spitzer and Bok to support a theory that such stars are being formed even now from interstellar matter. And he notes the connection between the age of the universe and the formation of the elements, the theory of which has recently been investigated by Gamow, Alpher, Hermann, Teller, Mayer, Klein, and others, based in part on geochemical studies of the relative abundances of the elements.

More interesting, probably, than such factual material is the sharp contrast between the various facets of our complex concept of time, illustrated so well in this series of lectures. In the third lecture of this volume, "Time and Historical Perspective," Professor Shotwell, of Columbia, describes the concept first in its use as a principle of ordering human lives, from the seasons to religious holy-days, then as the principle of sequence (chronology) in history—similar to its use in geology. From these ideas of time it is a far cry to the parameter, t, appearing in the equations of physics or to the age of the universe discussed by Professor Russell or to the intervals measured so accurately by modern timepieces. The last of these is covered in the fourth lecture, "Developments in Portable Timepieces," by Mr. George Luckey, of the Hamilton Watch Company, who discusses the practical problems of watch design, accurate measuring devices, and the development of materials suitable for use in timepieces.

It is quite clear, from this volume of four lectures alone, that the pursuit of time and all its mysteries will occupy the James Arthur Foundation lectures for some time to come.

THORNTON PAGE

University of Chicago

Volcanological Observations. By FRANK ALVORD PERRET. ("Carnegie Institution of Washington Publications," no. 549.) Washington: Carnegie Institution, 1950. Pp. ix+162; figs. 117. $5.00, paper cover; $5.50, cloth cover.

This posthumous monograph, closing number of an illustrious series (*Vesuvius 1906* [Pub. no. 339]; *Pelée 1929–32* [Pub. no. 458]; *Montserrat 1933–37* [Pub. no. 512]) is mainly a restatement and rearrangement of much of the author's previous observations. In contrast to the preceding reports, which dealt, respectively, with one volcano and one eruption, the present memoir takes us from volcano to volcano, from eruption to eruption. Following Perret through the pages of this book, we wander from Kilauea to Stromboli, from Teneriffe to Sakurajima, from Pelée to Etna and Vesuvius! Few men, if any, have spent forty years living through so many volcanic crises; none has left a more lively and convincing account of his varied and at times harrowing experiences.

The present volume is divided into eight chapters of unequal length and interest, dealing with, respectively: (1) the greater solid construction; (2) the volcanic liquid; (3) the gaseous element; (4) electric and atmospheric phenomena—volcanic vegetation; (5) volcanic ejectamenta; (6) gravitational and volcanoseismic phenomena; (7) experimentation, field and laboratory; (8) diagnosis and prediction. Emphasis throughout is descriptive and hard to summarize. The present reviewer finds it difficult to follow Perret to some of his conclusions, viz., diurnal stress variations due to lunisolar influences may have more than a trigger effect in touching off volcanic events; they are not without effect on the generation and maintenance of heat in the volcanic conduit (p. 130); invisible gas rising through the other material, whether liquid, ash, or visible vapor, draws it up

and after it, lifting it upward and outward rather than pushing it from below (p. 85); precipitation of ash directly from the vapor phase, by-passing the liquid state (p. 115). Emphasis is laid again, as in Perret's previous reports, on the importance of the "extension" property of the gas phase: it is gas compression, due to variable and sometimes rhythmic pressure pulses acting on vesiculated magma, which is responsible for the maintenance and perhaps regeneration of subcrustal terrestrial temperatures in the conduit of a surface volcano (p. 38).

Modern students of volcanic affairs may find it disappointing that, in spite of Perret's own statement that the fundamental nature of volcanism is thermodynamic, so little is to be found in this volume in the way of fundamental and exact theory or of quantitative estimates of the factors involved. Perret is neither a physicist nor a geologist; he is an observer and a photographer. He is not concerned, as he states at the outset, with the origin of volcanic materials or their mode of ascent; he is content to devote himself to their study "on our plane of existence." His account is therefore purely descriptive, and in this respect it is unmatched in volcanological annals. Perret has an extraordinary gift for clarity and sincerity which makes us feel that we see what he sees; and, seeing what he sees, we may well wonder at the astounding diversity of volcanic phenomena. Rightly does Perret emphasize again that "in the study of volcanoes nothing is more pernicious than the habit of generalizing in regard to time." As Stoppani has well said: "It should be understood that never will two persons who, visiting an active volcano, even in an interval of a few days, find it in the same condition"—and he might have said "*one* person." This diversity makes it all the more desirable that we should have accurate photographic records of volcanic events. As usual, Perret's illustrations are unsurpassed.

The publication of this beautiful monograph seven years after Perret's death is a fitting tribute to a great naturalist.

J. VERHOOGEN
University of California, Berkeley

Webster's Geographical Dictionary. Springfield, Mass.: G. & C. Merriam Co., 1949. Pp. xxxi+1293; tables 126; maps 177 (including 24 pls.). $8.50.

In this volume are listed in alphabetical order over forty thousand geographical names, including continents, countries, states, colonies, towns and cities, rivers, mountains, islands, lakes, deserts, canals, waterfalls, dams, parks, volcanoes, capes, and bays. Political status, location, area, population (in the United States as of the 1940 Census), geographic and physical features, economic and historical data, are given for countries, cities, and other political divisions. Such information as lengths and navigability of rivers, heights of mountains, areas of islands and lakes, and dates of discovery and colonization of various areas is included. There are twenty-four full-page maps in color, half of them historical in nature, and the others of the continents, larger island groups, the United States, Canada, and the British Isles. In addition, there is map of each state of the United States, of every country, and of the world's important cities and towns.

As a reference guide for correct spelling and pronunciation, the book should be particularly useful to the geologist who does considerable writing, editing, travel, or reading of foreign literature. In the latter connection it is helpful in getting in mind relative locations and magnitudes of physical features mentioned in passing, yet pertinent to the argument, in various geologic discussions of unfamiliar places. Of use in reading older foreign geologic literature is the inclusion of former names of various cities and areas; also useful is the inclusion of foreign names for cities in other foreign countries (i.e., Italian *Pola* for Yugoslav *Pulj*). The list of physical geographic terms in various languages, together with their English equivalents—for example, *gebel*, Arabic for "mountain," and *buketa*, Russian for "bay"—is also a helpful feature of the book.

LOU WILLIAMS PAGE
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COMMUNICATIONS AND ANNOUNCEMENTS

ENROLMENT OF GEOLOGISTS AND GEOPHYSICISTS IN THE NATIONAL SCIENTIFIC REGISTER

Planning for the mobilization and effective use of the scientists and engineers of the United States for purposes of national defense is now under way. Appointment of a committee composed of leaders in science and industry by the National Security Resources Board is a recent step. The representative of the geological professions on this committee is E. De Golyer; the chairman is Charles A. Thomas, vice-president of Monsanto Chemical Company and former president of the American Chemical Society.

A basic element in the entire program for maximum use of the nation's scientific manpower will be an adequate scientific register. This will tell us the magnitude and nature of the national pool of technological competence. In order to secure this information, the National Security Resources Board was instrumental last summer in causing the establishment of a National Scientific Register Office in the U.S. Office of Education. This office has let contracts with the American Chemical Society, the National Research Council, and the American Institute of Physics for enrolment of all physical and biological scientists and mathematicians. Enrolment will be accomplished through the societies, and the register will also be kept up to date through the societies. The American Geological Institute has been asked to insure the enrolment of all geologists and geophysicists.

The project must start essentially from scratch because the records of the World War II National Roster are completely out of date. Also, with the tremendous increase in the number of working scientists since 1945, its records are very incomplete.

Some geologists and geophysicists who are included in *American Men of Science* filled out a comprehensive registration form in 1948. These men *will not* be asked to answer all the questions on the new simpler form but will be asked to fill out basic questions in the interest of uniformity.

The following methodology is being established for this project to insure effective coverage. It is hoped that use of this method will spread the work, prevent wasteful and annoying duplication, and get the job done more promptly and effectively.

1. The register will include all geologists and geophysicists with a Bachelor's degree (or equivalent) and all graduate students.
2. Circularization will be accomplished by district committees. These will center in active local societies, state geological surveys, and major departments.
3. Each committee will be responsible for full circularization in its district and has been asked to estimate the number of forms required for this purpose.
4. Franked envelopes, requiring no postage, will be utilized. Where possible, these will be preaddressed.
5. Each form will be accompanied by a careful instruction memorandum.
6. A card file will be maintained in American Geological Institute headquarters, showing which forms have been completed and certain other pertinent data. The register will be used for the following purposes:
   a) By Scientific Advisory Committees in the Selective Service System. It is expected that these committees will review appeals for deferment which are made to the President and that the information on file with the register will be used in the consideration of such cases.
   b) By the National Security Resources Board. This agency is charged with responsibility for the planning of general mobilization, both military and civilian, and will use the information in determining the requirements for scientific manpower in various activities.
   c) By the National Research Council and by the American Geological Institute in determining the distribution and availability of earth scientists among the various specialized occupations.
   d) As a means whereby government agencies may identify personnel with specialized training or experience for unusual work requirements.

e) In the preparation of studies and recommendations to government agencies, such as the National Security Resources Board, concerning the needs for geological scientists in civilian occupations.

In addition, it will furnish information concerning the composition and structure of the geological professions, which will be invaluable.

The full co-operation of every member of the geological professions is earnestly requested, so that our part in this national effort may be performed quickly and effectively.

SEDIMENTOLOGICAL CONGRESS IN THE NETHERLANDS SUMMER, 1951

Two congresses on sedimentary and Quaternary geology have been held during the post-war years—the first in Belgium in 1946, the second in France in 1949. A third congress is being planned by a committee of Dutch geologists and sedimentologists and will be held in Groningen and Wageningen from July 5 through July 13, 1951. Because Quaternary geologists are planning their own meetings, the organizing committee thought it advisable to restrict the present congress to sedimentology in its broadest sense, e.g., methods of investigation and results of studies from all periods, problems of erosion, transport, sedimentation, and diagenesis.

Three days of the congress will be devoted to conferences and the remaining six to excursions. The main purpose of the excursions will be to show the variations in structure and texture of sediments of various environments.

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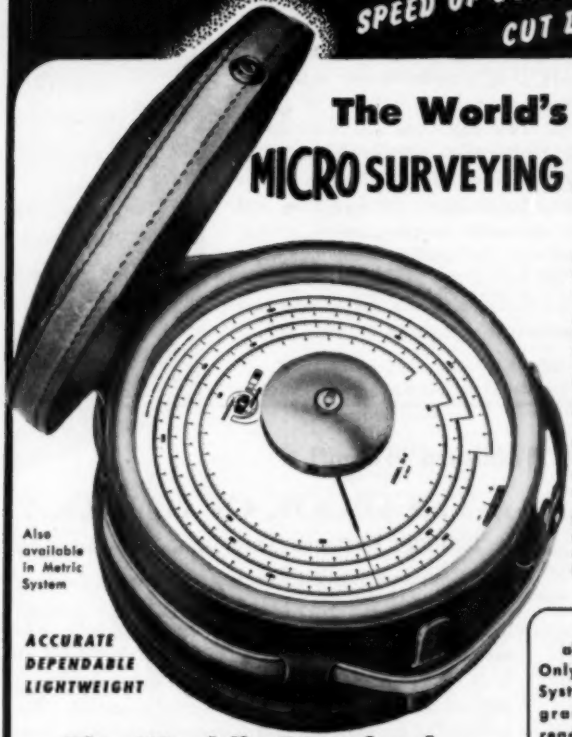

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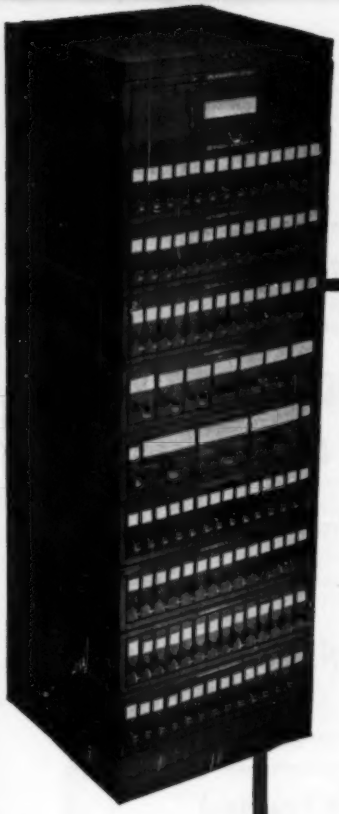

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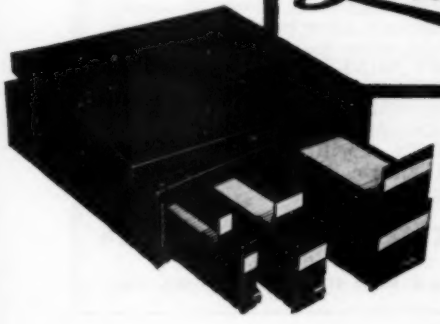

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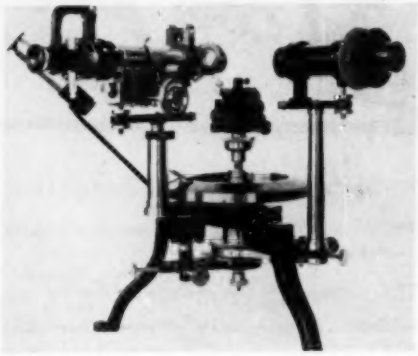

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